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THE BRIDGE

The Magazine of IEEE-Eta Kappa Nu

IEEE-Eta Kappa Nu

Fusion Energy's FUTURE

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The Magazine of IEEE-Eta Kappa Nu

2024 ISSUE 2 | Fusion Energy's Future

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Dr. Jason K. Hui

Epsilon Delta Chapter

"Fusion, which occurs naturally in the core of our Sun and stars, promises to provide abundant energy here on Earth without the harmful carbon dioxide and other greenhouse gas emissions caused by burning fossil fuels."

THE BRIDGE, May 2024

Letter from the Editor-in-Chief

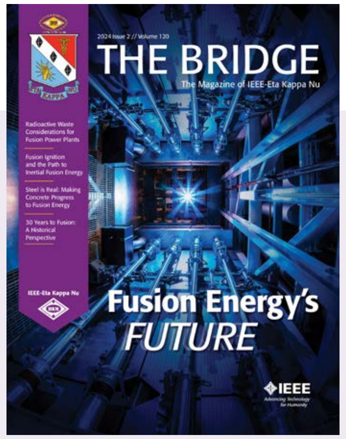
Dear IEEE-HKN Members and Friends,

This issue of *THE BRIDGE* magazine features the current state of activities and challenges in developing a sustainable energy source based on a controlled thermonuclear fusion reaction. Fusion, which occurs naturally in the core of our Sun and stars, promises to provide abundant energy (e.g., a pickup truck filled with fusion fuel has the equivalent energy of two million metric tons of coal, or 10 million barrels of oil [1]) here on Earth without the harmful carbon dioxide and other greenhouse gas emissions caused by burning fossil fuels. We express our gratitude to Editorial Board member and IEEE-HKN President-Elect, Professor Sean Bentley, for serving as guest editor and the authors of the feature articles.

This issue also recaps both Pathways to Industry and HKN TechX virtual events and previews the annual Student Leadership Conference slated for this fall. We encourage you to learn about this year's Alton B. Zerby and Carl T. Koerner Outstanding Student Award winner, Joseph Asouri, and the Outstanding Chapter Award recipients that were recognized at the Electrical and Computer Engineering Department Heads Association (ECEDHA) Annual Conference in Tucson and the winner of the HKN Best Student Paper Award at IEEE SoutheastCon 2024.

IEEE-HKN strives for effective communication through its various channels, including our website, YouTube, Facebook, LinkedIn, and this magazine. The Editorial Board welcomes your ideas and content and can be contacted by email at info@hkn.org. And as always, *THE BRIDGE* is available on the IEEE App (older archival issues can be found in the Engineering and Technology History Wiki).

1. DOE Explains...Fusion Energy Science | Department of Energy



About the Cover

The cover shows a color-enhanced image (rotated 90 degrees as shown) of the inside of a preamplifier support structure of Lawrence Livermore National Laboratory (LLNL)'s National Ignition Facility (NIF). The preamplifier support structures house key components for initial amplification and beam shaping for the optical pulses that ultimately come together to drive the fusion reactions. *Photo Credit: Damien Jemison*

Sean Bentley

Gamma Theta Chapter

"For the past several decades, the promise of a fusion future looked to potentially end the debate with what is often described as a nearly ideal energy source. In this issue, we will examine how close this fusion future might be, some challenges in getting there, and provide some perspective on the current prospect for fusion energy."

THE BRIDGE, May 2024

Intro from the Guest Editor

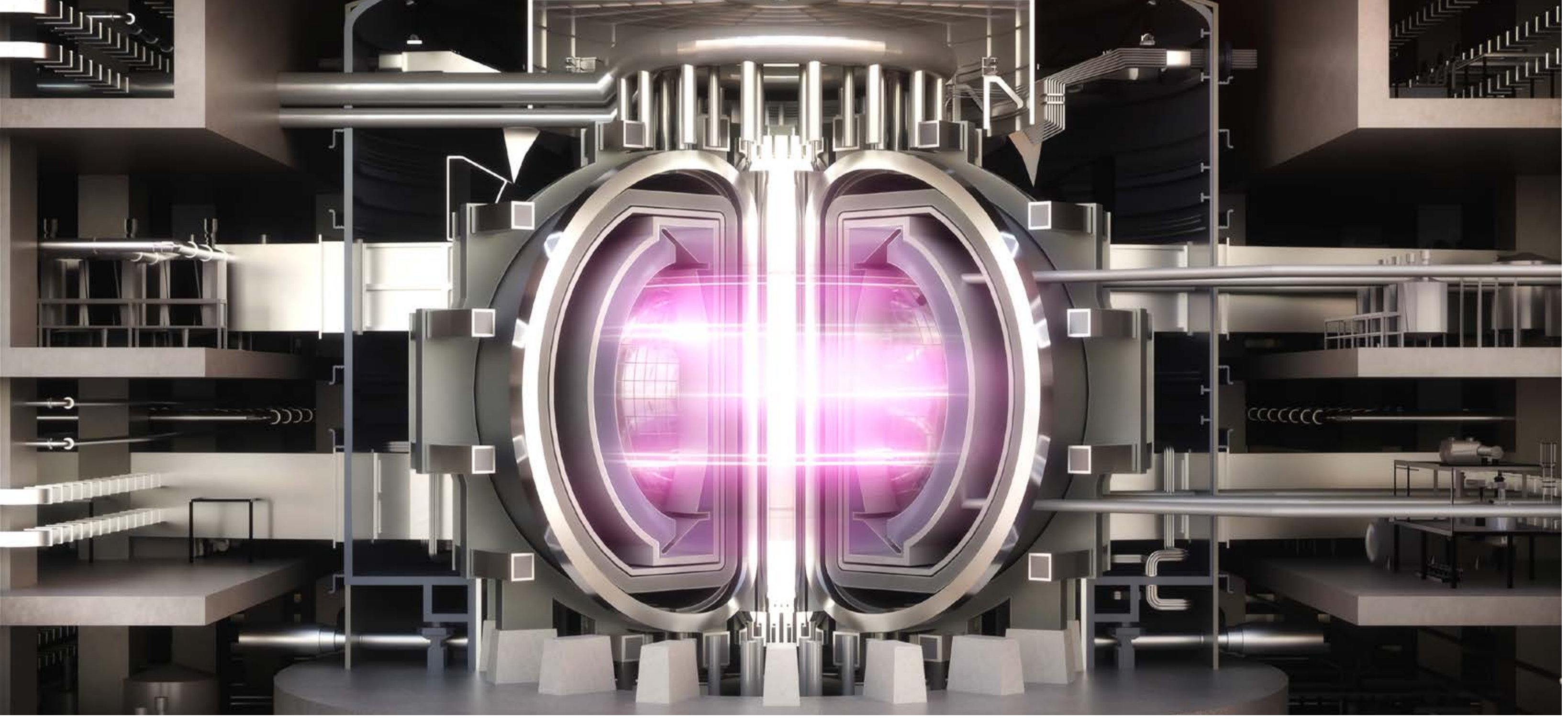
As many of you have surely seen, IEEE is celebrating 140 years in 2024. Founded as the American Institute of Electrical Engineers in 1884 [1], the organization started just two years after Edison's first power station opened and one year before power production and distribution began at Niagara Falls [2]. Electrical engineering and related fields certainly grew alongside the rise of widespread electricity generation and distribution. Since those early days, there have been many important sources of electricity, from fossil fuels to renewables to nuclear fission. Many factors, including cost, environmental effects, national energy independence, and more, cause the debate over the best source to continue. For the past several decades, the promise of a fusion future looked to potentially end the debate with what is often described as a nearly ideal energy source. In this issue, we will examine how close this fusion future might be, some challenges in getting there, and provide some perspective on the current prospect for fusion energy.

The History Spotlight delves into the notion that fusion energy is perpetually 30 years away, examining the advancements made and assessing the validity of this assertion. The achievement of ignition at Lawrence Livermore National Laboratory's National Ignition Facility (NIF) in late 2022 was one of the biggest fusion breakthroughs recently. The feature article "Fusion Ignition and the Path to Inertial Fusion Energy" examines the progress NIF has made and outlines the future challenges. "Radioactive Waste Considerations for Fusion Power Plants," another feature article, addresses the crucial issue of managing fusion-generated waste to avoid one of the major problems we face with fission. The rise of commercial fusion efforts is one indication that the future of fusion energy is much closer than ever before. The progress of one leading company, Commonwealth Fusion Systems, is described in our third feature article, "Steel is Real: Making Concrete Progress to Fusion Energy."

Earlier this month, educational and outreach activities were held across the country as part of the annual Fusion Energy Week (https://usfusionenergy.org/fusion-energy-week). Interest, advancements, and investments in fusion are all increasing. Will fusion energy soon become a reality? Will it live up to the promise of being a clean, nearly limitless energy source? You can read in this issue what many experts have to say about fusion energy's future.

1. https://www.ieee.org/about/ieee-history.html
2. https://americanhistory.si.edu/powering/past/prehist.htm

Sean J. Bentley earned his BSEE ('95) and MSEE ('97) from the University of Missouri-Rolla (now Missouri University of Science and Technology), and his Ph.D. in Optics ('04) from the University of Rochester. He is an Associate Professor of Physics at Adelphi University, where he was awarded the Teaching Excellence Award for 2012-13. He received the 2022 David Halliday and Robert Resnick Award for Excellence in Undergraduate Physics Teaching from the American Association of Physics Teachers. From 2014-2016, he served as Director of the Society of Physics Students and Sigma Pi Sigma (the physics honor society) at the American Institute of Physics. He served as the IEEE-HKN Regions 1-2 Governor for 2018-19 and a member of *THE BRIDGE* Editorial Board since 2021. He is the President-Elect of IEEE-HKN and an IEEE Senior Member.



Rendering of a prototype fusion power plant showing interior of the tokamak. Credit: General Atomics.

Radioactive Waste Considerations for Fusion Power Plants

Thomas W. Overton and Brian A. Grierson, General Atomics, San Diego, CA

Fusion energy is often promoted as generating little to no radioactive waste (radwaste). While it is true that fusion will not produce radwaste comparable to the highly radioactive spent fuel produced by fission reactors, without proper planning and engineering considerations, fusion plants have, on a per-megawatt basis, the potential to produce an order of magnitude greater volumes of low- and intermediate-level radwaste requiring disposal. These amounts are larger than current storage facilities can accept, but this issue has received scant attention in the current public focus on fusion, potentially imperiling general acceptance of fusion energy.

The challenge with fusion is two-fold: enhanced material activation due to much more energetic neutrons from the deuterium-tritium reaction, and tritiated materials generated by the use and handling of large amounts of tritium during operation. Past work, as well as experience with facilities such as the Tokamak Fusion Test Reactor, suggests these challenges can be addressed by: 1) using materials designed to reduce activation to the lowest practical level; 2) designing plants to limit production of radwaste; and 3) recycling activated/tritiated materials within the industry. To support public acceptance and avoid repeating past mistakes by the fission industry, a fusion regulatory regime should require plant developers to design for minimal radwaste production, encourage recycling, and facilitate clearance of activated materials that pose no public health risk.

Introduction

Fusion energy, once the province of science fiction, has experienced enormous progress over the past decade, both in resolving the many physics and engineering challenges to commercial power plants and in growing public awareness of its potential [1, 2]. The potential advantages of fusion energy over current methods of electricity generation are considerable. One of the components of the fuel, an isotope of hydrogen called deuterium, is readily available. The other component, another hydrogen isotope called tritium, will be produced as part of the fusion reaction. The by-products of the deuterium-tritium (D-T) reaction are helium and an energetic neutron. Like a gas, coal, or nuclear fission plant, a fusion power plant could operate around the clock, without producing harmful emissions or dangerous transuranic radioisotopes. The risk of accidents with a fusion plant is very limited. The fuel must be contained under precise, specific conditions to create fusion, and if this containment is lost, the reaction simply stops. Though fusion is not risk-free, wide-scale releases of energy are not possible.

However, one element that can be glossed over in public communication efforts promoting fusion energy is the amount of radwaste that would be produced by a large-scale commercial fusion power plant. Communications typically focus on the avoidance of long-lived, high-level waste issues to contrast fusion with existing fission plants. Fission energy, which uses uranium-235, generates a regular stream of spent fuel assemblies that require careful handling and either long-term storage or expensive and problematic reprocessing. This is because of the radionuclides that are a by-product of the uranium fission reaction, some of which remain dangerously radioactive for hundreds or thousands of years.

Fusion plants operating with materials that avoid specific elements presenting activation risks (e.g., carbon, nickel, niobium, and molybdenum) will not produce long-lived radioisotopes nor any high-level radwaste. They will, however, produce as much as an order of magnitude greater volumes of *low-* and *intermediate*-level radwaste that will require some means of disposal [3]. The amount of radwaste that would be produced by a fleet of fusion plants exceeds the capacity of existing storage facilities [4].

The different characteristics of fusion radwaste are due to the significant differences between the uranium fission reaction and the D-T fusion reaction, as well as the differences in construction between fission and fusion reactor vessels. Fission plants contain the reaction within a relatively small core, where the uranium fuel is sealed inside metal rods. In normal operation, fission by-products are contained within the fuel rods and do not interact with other elements of the plant.

Most magnetic and laser inertial fusion concepts, by contrast, will use a much larger vacuum vessel to contain the fusion plasma. Tritium fuel must be continually added to the plasma as well as removed from a breeding system during operation. A key feature of the D-T reaction is that it generates a highly energetic 14-MeV neutron that carries significantly more energy than the neutrons generated by uranium fission (most are under 3 MeV). These neutrons will penetrate surrounding structures and activate elements used in their construction. While few of these elements can be converted to long-lived (>100 y half-life) radionuclides, the induced activity levels are high enough to implicate radwaste disposal concerns.

Fission plant cores are also activated in this manner during operation. However, because of the much larger volume of the fusion core, fusion plants will generate much more of this low- and intermediate-level radwaste. In addition, because hydrogen reacts so readily with other elements, fusion fuel system components will absorb tritium, and this tritiated material will also require treatment or disposal.

Materials Challenges for Fusion

An example of a typical magnetic fusion reactor is shown in Figure 1.

First Wall and Blanket Materials. One of the key challenges to economical fusion energy is the need for materials that can survive the extreme conditions in and around the fusion plasma [5, 6]. This includes the "first wall" of the plasma chamber, that is, the surface that will be directly exposed to the fusion plasma, as well as the area outside it, known as the blanket. The blanket attenuates the neutrons and gamma rays, resulting in their capture and conversion of their kinetic energy to heat. The blanket also houses elements of the systems that breed and collect tritium and extract heat for use in power generation.

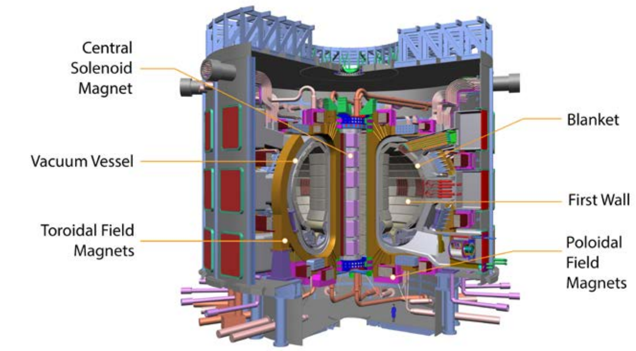


Figure 1a. Cross-section of a magnetic fusion tokamak showing components of concern for activation.

Figure 1b. Internal view of the tokamak at the DIII-D National Fusion Facility in San Diego.

All these components will be exposed to extremely high temperatures and particle bombardment, as well as periodic cycling. The first wall will need to be protected by an especially durable material with a high melting point and low erosion, such as tungsten. The high temperatures in this area mean certain components need to be manufactured from ceramic rather than metal.

Beyond the blanket are additional power generation equipment, the superconducting (SC) magnets used to create the magnetic containment fields, and other control systems. Many of these components, particularly the SC ceramics used in the magnets, can be seriously damaged by radiation from activated materials around the reactor. Thus, this area must incorporate a radiation shield. A cross-section is shown in Figure 2.

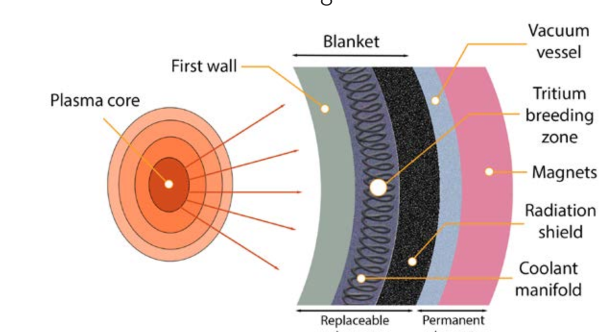


Figure 2. A cross-section of a tokamak vessel showing the plasma and components that are exposed to neutron and other radiation during operation.

Tritium Breeding. To be economic, D-T fusion plants will need to breed tritium during operation, as naturally occurring tritium is too rare to serve as an external fuel source and existing methods of manufacturing tritium present far too great a cost element. In this, the 14 MeV fusion neutron provides a potential solution, as it can react with lithium-6 to produce helium and tritium. The challenges with such an approach are considerable, however. The tritium breeding system must withstand continual bombardment by fusion neutrons while safely containing, extracting, and storing the generated tritium. Lithium is highly reactive and typically combined with another material like lead as a neutron multiplier and for safer handling.

A fusion tokamak will operate at high temperatures (potentially exceeding 1000 °C at the first wall), in which lithium and lead will be in liquid form. These temperatures potentially allow for much higher efficiencies than pressurized water–based fission plants can achieve, which would improve the economics of a commercial plant. Accessing these temperatures, however, requires more challenging coolants such as high-pressure helium, and helium is notoriously difficult to contain because the atoms are so small. A helium-based heat off-take system must be effectively impermeable to helium during normal operation, which further limits the potential materials that can be used.

Characteristics of Fusion Radwaste

Structural Materials. Activated structural materials represent the largest source of potential fusion radwaste [7]. Some studies estimate that current designs for large-scale fusion power plants could generate as much as 10,000 tons of low-level waste just from tokamak components alone [8]. Many common alloying elements and impurities in structural steels can be activated by fusion neutrons. These include molybdenum, nickel, carbon, copper, aluminum, and niobium, as well as impurities such as cobalt, potassium, and silver. Carbon, nickel, niobium, and molybdenum present particular concern because some isotopes have half-lives over 100 years (e.g., carbon-14, nickel-59, nickel-63, and niobium-94).

Tritiated Materials. Some designs for tritium breeding systems incorporate beryllium as a neutron multiplier or moderator to enhance tritium production. While beryllium itself is not a material of radiological concern, beryllium can contain trace amounts of uranium. If significant amounts of beryllium are used, the level of uranium present can rise to the point of creating transuranic isotopes above regulatory thresholds [9]. Furthermore, beryllium requires special health, safety, and handling equipment because of its toxicity.

The lithium-lead fluid used in the tritium breeding system is another area where design for reduced waste will be necessary. Activation of the lead will create radioactive by-products such as mercury-203 and polonium-210. While both have relatively short half-lives, their activity levels will require a system to remove them during operation. Storage and handling measures will also need to be in place for these materials.

Nearly all components of the tritium fuel cycle have the potential to absorb tritium during operation. While tritium is not as significant a concern as other radionuclides due to its low-energy beta emission, it has the potential to enter groundwater if not properly contained. Existing low-level waste repositories are not designed to handle large amounts of tritium. Tritium is also an element with non-proliferation concerns due to its use in nuclear weapons design, which creates complications for storage and disposal.

It is important to recognize that while structural materials will not require treatment or disposal until decommissioning, other elements of a fusion reactor will be replaced and removed on an ongoing basis during operation. This will notably include the areas that will be subjected to the highest radiation levels, such as first-wall components and elements of the blanket that cannot be expected to survive over the life of the plant. This waste stream will need to be managed through proper design to keep volumes at a minimum.

Mitigation and Disposal Methods

The fission generation industry has benefited from decades of design optimization intended to simplify decommissioning, reduce radwaste, and ensure a range of economical decommissioning options for plant owners. Because current fusion devices are much smaller than future power plants, and typically conduct experiments with D-D fusion (which produces a much lower neutron flux), this process is incomplete for fusion. However, there are several relevant lessons learned from fission that can be applied to fusion power plants.

A key difference between fusion and fission is that fusion radwaste is not inherent to the fusion reaction the way fission by-products are. Thus, the volume and characteristics of fusion radwaste are considerably more controllable through appropriate design and operational best practices. The fusion community has considered a range of options to reduce the production of radwaste during operation, recycle activated materials where possible, recover tritium from tritiated components, and safely store or dispose of materials that cannot be recycled.

Reduced Activation. Structural steels used in current fission plants, especially stainless alloys with significant nickel content, are inappropriate for fusion because of the activation risks. These alloys are also unsuitable due to their insufficient radiation resistance and performance at high temperatures. Thus, fusion reactor designers have focused on steels specifically designed to limit activation to the greatest extent possible.

The primary current candidate is reduced-activation ferritic martensitic (RAFM) steels developed specifically for fusion applications. RAFM steel is based on the composition of high-chromium heat-resistant steel, but it replaces alloying elements of potential activation concern. Molybdenum is replaced with tungsten and niobium with tantalum, and no nickel is used.

However, current RAFM steel has an operational temperature ceiling of 550 °C, which means it cannot be used for components that are expected to withstand higher temperatures. Alloys with higher temperature ceilings are under development but are not yet mature.

It is important to note that even RAFM steel contains niobium and nickel as impurities, as well as carbon. High-purity manufacturing processes will be necessary to reduce impurities to the lowest practical levels.

The highest-temperature areas of the reactor vessel will need to rely on more exotic materials such as silicon carbide, tungsten and vanadium alloys, and the like. These materials possess high durability and low activation potential but are of lower maturity for fusion applications and may present potentially unattractive cost elements for prospective plant developers.

Recycling. The fission industry has demonstrated that recycling radwaste can be economically attractive as well as reduced burdens on storage facilities, and both the U.S. Nuclear Regulatory Commission (NRC) and Department of Energy have experience with such efforts. Many of the activated or tritiated components of a fusion plant could potentially be recycled within the plant, in a replacement plant, or in another appropriate facility [10]. Experience with retired experimental fusion facilities suggests many of the potentially problematic materials are suitable for recycling. In the U.S., the Tokamak Fusion Test Reactor at Princeton Plasma Physics Laboratory, which conducted D-T experiments in the 1990s, incorporated recycling and reuse as part of its successful decommissioning process.

A robust recycling ecosystem for fusion energy would alleviate many potential problems with fusion-generated radwaste. However, developing this ecosystem will implicate many practical issues and engineering hurdles. Tools will need to be developed for remote handling of radioactive components, especially those that are replaced regularly. Procedures need to be developed for the separation of activated elements from inactive elements, as well as for the separation of radionuclides where feasible.

Recycled materials must be economically attractive to the industry. Certain recycled components or materials may be less expensive than new ones, or they may present an economic disincentive due to necessary processing or treatment. In the latter case, costs could be reduced once efficient processes are in place and the supply chain has more expertise in handling activated materials.

Detritiation. Tritiated components present a special challenge for recycling and disposal because of hydrogen's high mobility and reactivity. While detritiation of these components is possible, experience from the fission industry has demonstrated that tritium can easily migrate during processing and disposal. Because the primary health risk from tritium is via ingestion, measures must be taken to prevent it from entering groundwater. Tritium's 12-year half-life means that decades-long, in-situ decay storage is likely to be an element of future radwaste management. Current NRC guidelines allow this sort of storage for fission plants prior to decommissioning, and a similar approach can be expected for fusion.

Clearance. Finally, a significant amount of fusion radwaste, while mildly radioactive, will have activity levels that are below limits necessary to protect public health. Clearance by regulatory authorities is necessary for these materials to be released from oversight, but doing so will require fusion plant operators to develop inspection, processing, and management practices that can separate this low-level radwaste from more radioactive materials requiring different handling.

Regulatory Issues

For several decades, the fusion science community has been in general agreement on the necessity of focusing on reducing the volume of radwaste production during the life of a power plant [11, 12]. However, this agreement may not be as extensive within the private fusion community, given their need to deliver a return to investors within projected timeframes for commercial fusion and the low maturity of advanced materials such as silicon carbide.

The NRC, the United Kingdom Atomic Energy Authority (UKAEA), and other national regulatory bodies are in the process of developing regulatory regimes for fusion energy. The NRC has stated that it plans to adapt existing regulations for nuclear by-product facilities rather than the current regime for fission plants [13]. The UK government has stated that it will proceed under existing rules governing experimental fusion facilities in the UK [14].

Regulations for by-product facilities, however, do not anticipate anything close to the amount of radwaste that fusion plants will produce. In addition, current regulations governing the disposal and storage of radwaste are primarily focused on handling such waste after it has already been produced. While existing disposal regulations will need to be adapted to the fusion industry, it would be beneficial if rules for licensing of fusion facilities incentivized design for radwaste reduction.

Existing regulatory regimes that allow for clearance and release of low-level materials are designed for fission plants and other industries, and they may not be optimal for the unique characteristics of radwaste produced by fusion plants. Fusion regulatory regimes will need to establish efficient clearance rules that sufficiently protect public health. The importance of establishing best design practices that prioritize reduced production of fusion radwaste cannot be overstressed. Designs that produce the least amount of radwaste will make downstream clearance processes much less onerous.

Conclusion

The success of fusion energy will require coordinated strategies to avoid burdening operators and disposal facilities with impractical volumes of low- and intermediate-level radwaste. Poor strategies and a lack of agreement around long-term waste management resulted in serious damage to public acceptance of fission energy, and it is important for fusion energy to avoid these mistakes. Designers, industry, and regulators will need to work together to develop the necessary regulations and best practices. A sound regulatory regime should require and incentivize the use of low-activation materials, promote recycling and reuse paths, and allow for clearance processes that protect public health.

Thomas Overton is Senior Strategic Development Specialist with General Atomics in San Diego. He supports GA's inertial and magnetic fusion energy programs by pursuing new opportunities and applications for the company's world-leading R&D efforts, as well as managing the group's patent portfolio.

Brian Grierson is Director of the Fusion Pilot Plant Design Hub for General Atomics. As part of GA's magnetic fusion energy team, he leads scientists and engineers in developing integrated fusion pilot plant designs and technology to put clean, safe, and economically viable electricity on the grid.

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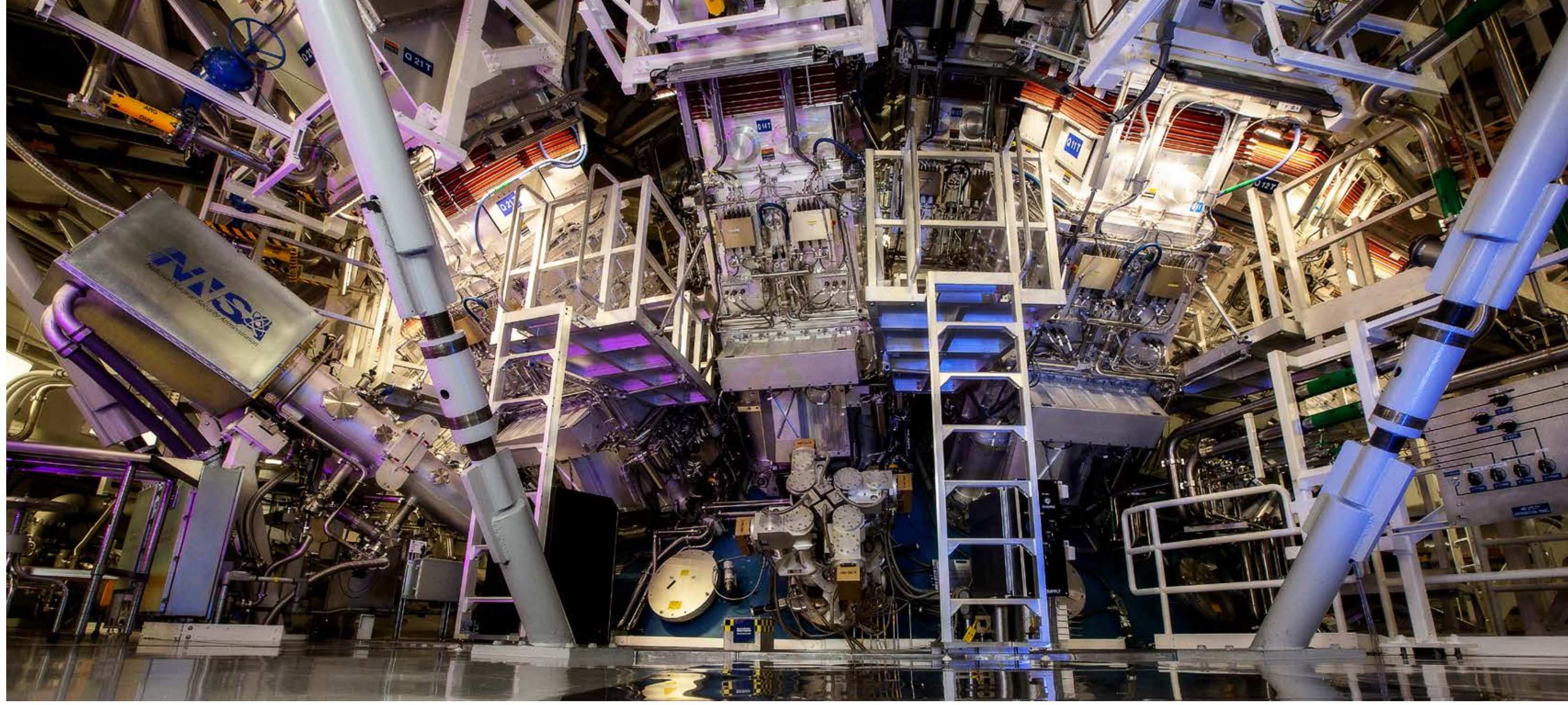

View of the NIF Target Chamber from the Target Bay. NIF's 192 laser beams converge at the center of the giant sphere to make a tiny hydrogen fuel pellet implode. Credit: Jason Laurea

Fusion Ignition and the Path to Inertial Fusion Energy

Charlie Osolin, Lawrence Livermore National Laboratory

The achievement of fusion ignition at Lawrence Livermore National Laboratory's (LLNL) National Ignition Facility (NIF) in December 2022 was the culmination of more than 60 years of research and development in laser-driven inertial confinement fusion at LLNL. That historic scientific, engineering, and technological accomplishment, a prime example of the value of ingenuity and commitment in the face of a grand scientific challenge, marked a significant advance in LLNL's support of the National Nuclear Security Administration's science-based Stockpile Stewardship Program to maintain the reliability and security of the nation's nuclear deterrent without underground testing. It also furthered Livermore's research in high energy density science and established the fundamental scientific basis for inertial fusion energy (IFE), emboldening further public and private research into the development of IFE as a potential source of abundant clean, safe, and reliable energy. The U.S. government has funded a multi-disciplinary, multi-institutional program that LLNL is now leading to make inertial fusion energy a reality.

I. Introduction

The U.S. Department of Energy's (DOE) Lawrence Livermore National Laboratory made scientific history on December 5, 2022. An experiment at NIF achieved "target gain,"producing more energy from nuclear fusion (3.15 MJ) than the amount of laser energy delivered to the fusion target (2.05 MJ)—a metric for achieving a robustly ignited fusion plasma [1-3]. An international team of scientists, engineers, technicians, and support staff has compared the groundbreaking achievement to the first powered flight by the Wright Brothers. Four additional ignition shots followed the December experiment: July 30, 2023; October 8, 2023; October 30, 2023; and February 12, 2024. The most recent experiment produced an estimated 5.2 MJ—more than doubling the input energy of 2.2 MJ. Additional experiments using higher laser energies and producing even higher energy yields are expected in the coming months, further demonstrating that NIF can repeatedly conduct fusion experiments at multi-megajoule levels of energy output [4].

Nuclear fusion is the process that powers the sun and other stars, where gravitational forces provide the natural confinement, compression, and heating required for fusion. Other than at NIF, the world's largest and highest-energy laser, these conditions only occur on Earth in an exploding thermonuclear weapon. The results of NIF ignition experiments enable researchers to assess the performance of nuclear weapon systems and perform weapon science and engineering calculations. This is a key element in the DOE National Nuclear Security Administration's science-based Stockpile Stewardship Program to ensure the safety and reliability of the nation's nuclear deterrent in the absence of underground weapons testing [5].

Another important LLNL/NIF mission is to explore the possible use of nuclear fusion as a future energy source. By 2050, projections indicate a nearly 50 percent increase in worldwide energy consumption [6]. An energy technology revolution and breakthrough concepts are needed to decarbonize the world's energy system and stabilize the climate. Fusion has the potential to provide a reliable, abundant, safe, and clean source of electricity. The repeated achievement of fusion ignition at NIF has established the fundamental scientific feasibility of laser-driven inertial confinement fusion (ICF) as a path toward fusion energy—a potentially transformative technology that could produce electric power without carbon emissions, long-lived nuclear waste, or the risk of meltdowns. Fusion researchers around the world, in government laboratories and the private sector, are now working to develop the technology to generate electricity through fusion [7, 8]. The achievement of target gain at LLNL, along with overall progress in magnetic fusion and other confinement schemes, has set the stage for a national and international effort to move fusion energy from the laboratory to the marketplace. The lessons learned from LLNL's ignition experiments are helping lay the groundwork for constructing, in the foreseeable future, IFE-based power plants [9].

II. Achieving Fusion Ignition

Demonstrating, and then repeating, fusion ignition in the Laboratory arrived after six decades of research into laser-driven ICF at LLNL [10]. Following the invention of the laser in 1960, Livermore developed a succession of ever-higher-energy laser systems, culminating in the construction of NIF, a 192-beam laser system capable of exceeding the extremes of pressure and temperature that exist in the centers of stars [11].

Figure 1. LLNL has achieved fusion ignition on NIF five times to date.

Scientists, engineers, and technicians had to overcome a daunting array of challenges in designing and constructing NIF. Working closely with industrial partners, the NIF team found solutions for NIF's optics in rapid-growth crystals, continuous-pour glass, optical coatings, and new finishing techniques that can withstand NIF's extremely high fluences. The team also worked with vendors to develop pulsed-power electronics, innovative control systems, and advanced manufacturing capabilities. Known as "The Seven Wonders of NIF," the team introduced these enabling technologies as the facility was being built [12]. Similar technical breakthroughs will be required in the international effort to develop fusion energy power plants.

Expectations for ignition on NIF within a year or two of its dedication were high, but the first ignition experiments, beginning in 2011, fell well short of the predictions derived from computer models. The experiments produced only one to two kilojoules of energy which is a small fraction of the 1.8 MJ fired into the pencil-eraser-sized cylinders called hohlraums that held NIF's tiny plastic target capsules filled with frozen deuterium and tritium [13]. The implosions were unstable, asymmetric, and had a high level of energy-sapping laser-plasma interactions (LPI).

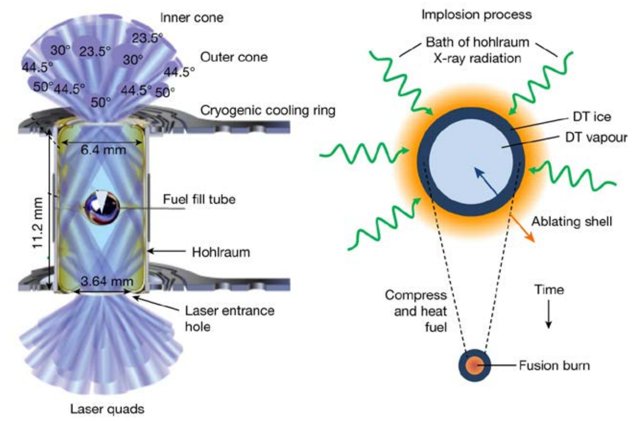

Figure 2. A typical NIF indirect-drive target configuration. At left, laser beams (blue) enter a pencil-eraser-sized cylinder called a hohlraum through laser entrance holes at various angles. At right, at the center of the hohlraum, the target capsule, filled with a thin layer of cryogenic deuterium-tritium (DT) fuel and a volume of DT gas, is bathed in X-rays. The X-rays heat and blow off, or ablate, the outer surface of the capsule, causing a rocket-like implosion that compresses and heats the fuel in the capsule's central "hot spot" to the densities and temperatures required to fuse the atoms. The resulting fusion reactions create high-energy alpha particles (helium nuclei) that accelerate into and heat the cold fuel surrounding the hot spot, generating an explosive, self-sustaining fusion reaction that leads to ignition.

Over the subsequent 10 years, the models and the ability to interpret them improved, and the researchers benefited from an ever-growing knowledge base provided by NIF's sophisticated diagnostic equipment, improvements in laser energy balance, optics, and targets, and new experimental designs based on lessons learned from earlier experiments. The impediments to successful implosions—asymmetries, LPI, fuel contamination by target capsule material, radiative losses, laser backscatter and hot-electron production, and other instabilities—were gradually overcome [14].

Reaching ignition was made possible by contributions from the NIF laser, operations, diagnostics, optics, and modeling teams and the Livermore and General Atomics target fabrication teams; scientists, engineers, technicians, and administrative and support personnel from throughout the Laboratory; and extensive collaborations with researchers in the world's fusion, plasma physics, and high energy density (HED) science communities in other national laboratories, universities, and industry. ICF researchers intend to build on the recent results by increasing energy coupling to the targets, and then understanding and correcting the limitations presently observed with respect to compression [15].

Achieving ignition, a case study in the value of innovation and persistence in the face of a demanding scientific challenge, garnered world-wide attention and excitement: the foundational basis for generating energy from controlled fusion had been demonstrated. To date, more than $6 billion of private funding has been invested in the global fusion industry, and the number of commercial fusion companies has grown to more than 40 [16]. But the question remains: When will fusion energy be available to power our homes and businesses? The answer depends on the level of resources brought to bear on the problem, the extent of worldwide public- and private-sector collaboration, the pace of technology development, and—as in the case of ignition—the dedication and creativity of the world's fusion community.

III. Fusion Energy Challenges

NIF is an experimental facility; it was not designed to be efficient or to produce power. The NIF laser architecture and target configuration were chosen to give the highest probability for fusion ignition for research purposes and were not optimized to produce net energy for fusion energy applications. For example, the fusion reaction produces only a fraction of the energy needed to fire the facility's 192 powerful laser beams.

Significant technical and political challenges remain, therefore, in translating fusion ignition from a laboratory experiment to a viable commercial power plant [17]. Fortunately, however, several components of the NIF laser system, as well as LLNL's expertise in other key aspects of ICF, can provide a kick-start for developing the technology for an integrated power plant (Figure 3). And the same fusion plasmas created on NIF for national security applications can also be exploited to be the basis of IFE physics.

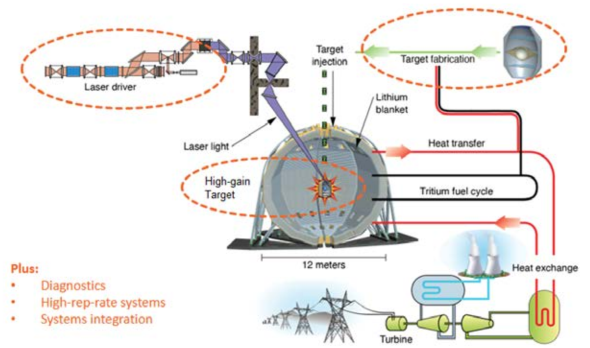

Figure 3. Schematic of a potential IFE power plant; the orange circles and text denote areas of LLNL expertise. A laser fusion power plant would use high-powered lasers to create continual fusion ignition reactions from a steady stream of hydrogen pellets. These pellets, which contain the hydrogen isotopes deuterium and tritium, would be fired into the plant at a rate of approximately 600 per minute. The plant's lasers would precisely converge on each pellet, causing them to ignite and give off 50 to 100 times more energy than went in. That excess energy could then be converted into a clean, abundant source of electricity and connected to the power grid. Laser fusion power plants would likely be about the size of a small football stadium, and just one could meet the energy needs of a city the size of Washington, D.C.

Developing an economically attractive approach to fusion energy is a grand scientific and engineering challenge that will require the same level of sustained commitment that characterized the quest for ignition. Fusion power plants will require the integration of multiple complex subsystems, as well as factoring in cost and efficiency into their design. Areas that will require significant additional technology development include:

- Efficient drivers capable of achieving net energy gain (more energy produced than the energy required to operate the reactor).
- The ability to fire the driver at a repetition rate of 10 Hz or more to provide a continuous stream of energy to the power plant.
- Enhancing understanding of the complex physics of burning plasmas.
- Designing high-gain targets capable of emitting 50 to 100 times the input energy.
- Mass-producing robust, high-quality, and inexpensive targets at a rate of nearly one million per day for a power plant shot rate of 10 Hz.
- Developing a lithium blanket for converting the heat from the fusion reactions into usable energy and for breeding tritium.
- Constructing materials able to withstand the reactor's intense radiation environment.
- Taking advantage of emerging technologies such as exascale computing, artificial intelligence, machine learning, and advanced manufacturing.
- Training the future workforce.
- Instilling public confidence in the benefits and safety of fusion energy.

These and other challenges were explored in a series of workshops and reports [18-23] that followed LLNL's breakthrough experiment on August 8, 2021, that moved NIF to the threshold of ignition [24].

IV. The Path Forward

Building on LLNL's demonstration of fusion ignition in a laboratory, the U.S. government is now taking concrete steps to make inertial fusion energy a reality. Achieving ignition gives the United States a "unique opportunity" to further lead the world scientific community's pursuit of developing fusion as a future source of clean energy, according to a February 2023 IFE Basic Research Needs (BRN) report from DOE's Office of Science. "The formidable scientific and technological challenges that lie ahead before fusion energy becomes fast, efficient, economical, and reliable enough can be overcome," the report said, "with expanded, coordinated research, development, and deployment programs and strategic public-private partnerships" [25, 26]. The BRN report provides a set of priority research opportunities that can inform IFE efforts.

Recognizing that the U.S. needs to capitalize on its current leadership in ICF to move from ignition to practical fusion energy, Livermore established a new IFE institutional initiative in 2022 to help support and grow the national program and community. The initiative also seeks to strengthen science, technology, and engineering capabilities through a strategy of multi-institutional partnerships [27].

In May 2023, DOE announced awardees to a $46 million milestone-based fusion development program that emphasizes public-private partnerships through government support and private company cost-share as a first step toward realizing the Biden administration's Bold Decadal Vision for commercial fusion energy [28]. Under this milestone program, private companies are leading the development of designs for fusion pilot plants.

And in December 2023, DOE announced awards in a $42-million program to establish three multi-institutional and multi-disciplinary hubs to advance foundational IFE science and technology. This effort, the Inertial Fusion Energy Science and Technology Accelerated Research (IFE-STAR) program, brings together expertise and capabilities across national labs, academia, and industry to address priority research opportunities for IFE [29].

IFE-STAR includes a four-year, $16 million project for LLNL to accelerate IFE science and technology through the IFE Science and Technology Accelerated Research for Fusion Innovation and Reactor Engineering Hub, or STARFIRE [30]. STARFIRE Hub partners are working together to develop systems-level laser architecture, plant-compatible target designs, and a plant-assessment framework.

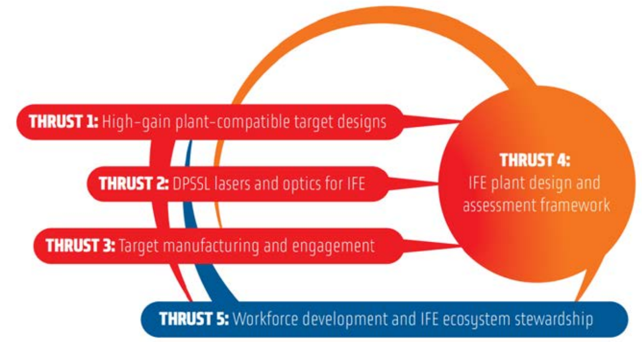

Figure 4. The IFE-STARFIRE hub will accelerate technology and workforce development to advance fusion energy research.

STARFIRE's efforts will develop foundational science and technology to support the growing public and private IFE communities. STARFIRE will accelerate the demonstration of high-gain target designs, target manufacturing, tracking, and engagement, as well as diode-pumped solid-state laser (DPSSL) technologies, with the development of these technologies guided through an IFE plant-modeling framework. The project will also begin developing the IFE workforce of the future through partnerships with leading universities and innovative curriculum development and implementation.

The hub consists of members from seven universities, four U.S. national labs, one international lab, three commercial entities, one philanthropic organization, and three private IFE companies. Two other hubs were also awarded, led by Colorado State University and the Laboratory for Laser Energetics at the University of Rochester. Together, the three hubs are helping to lay the foundational groundwork for laser fusion energy prototype plants in the coming decade in support of DOE's Bold Decadal Vision for Fusion Commercialization.

V. Summary and Conclusions

In collaboration with the international ICF, plasma, and HED research communities, Lawrence Livermore National Laboratory has successfully completed its 60-year pursuit of fusion ignition in a laboratory. Four subsequent experiments also succeeded in producing more energy from a laser-driven ICF implosion than the laser energy required to initiate the fusion reaction, enabling researchers to study new regimes in HED physics that are important to LLNL's stockpile stewardship mission.

For many decades, the running joke in fusion research was "fusion is 20 years away and always will be." Yet ICF researchers are now able to refer to the milestones of burning plasmas, fusion ignition, and target energy gain greater than unity, or "scientific breakeven," in the past tense. With proof of fusion ignition and scientific breakeven in the laboratory, Livermore's next challenge is to help lead a national and international effort to apply the lessons of ignition in the quest to make fusion a source of abundant clean, safe, and reliable energy. Inertial fusion energy has the potential to be a game-changing technology for deep decarbonization while bolstering American science and technology leadership, security, and energy independence. With funding from the U.S. government and in collaboration with the private sector, the prospect of powering the world's homes and businesses with fusion energy is no longer a distant dream. Substantial challenges remain, but the future of ICF and fusion energy could not be brighter.

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Steel is Real: Making Concrete Progress to Fusion Energy

Dan Brunner, Commonwealth Fusion Systems, Devens, MA

Introduction

The novel superconducting magnets holding a 100 million degrees Celsius plasma in place may make fusion seem like an almost unapproachable science fiction energy source [1]. Yet, much of the support equipment and facilities for a fusion energy plant would not look out of place at a normal power plant or particle accelerator. These systems, while challenging, are within the scope of well-established engineering disciplines. For fusion to work, not only must it produce net power and electricity, but it also must do so in a way that is economically competitive with other energy sources. Commonwealth Fusion Systems (CFS), a spin-out of the MIT Plasma Science and Fusion Center, has built a team and an organization to do just that: turn the science fiction of fusion energy into an economic reality. The team is working on SPARC, a compact high-field tokamak. This is the first major step on the path that integrates the new superconducting magnet technology into a first-of-its-kind demonstration of commercially relevant net fusion energy production. Today, CFS is finalizing the engineering designs for SPARC. Equipment is being built at CFS and by our supply chain partners, and installed at the SPARC site in Devens, Massachusetts.

Handling extreme heat – and extreme cold

A series of nested components supports the superconducting magnets in enabling the machine's core to make fusion-grade plasmas. These systems are much like those used for decades in particle accelerators. Starting from the plasma outwards, there are: the plasma-facing components, which handle the extreme heat fluxes from the plasma; the vacuum vessel, which creates a clean, pure environment in which to ignite and sustain the plasma; the superconducting magnets, which confine and control the plasma; and the cryostat, which provides a cold environment for the superconducting magnets.

Plasma-facing components

The plasma-facing components are the first things the plasma "sees" inside the fusion device. This is one of the most challenging interfaces where 10,000°C to 1,000,000°C plasma is in direct contact with a solid material. It is a battle to tame the plasma so that it doesn't melt the surface or erode it too quickly. The areas with the highest heat flux in SPARC will need to survive transient surface heat fluxes well in excess of 200 MW/m^2 (for comparison, the heat flux at the surface of the sun is ~60 MW/m^2). Very few materials can survive in such an environment, with the primary option being tungsten. Tokamaks, including SPARC's predecessor, Alcator C-Mod at MIT, have a proven track record of using tungsten as a plasma-facing component.

In many ways, pure tungsten makes an excellent plasma-facing component; it has the highest melting point of all metals (3,422°C) and a very high thermal conductivity (>100 W/m/K), as well as being relatively robust against plasma erosion and neutron transmutation. Yet, it is also a very brittle material and challenging to machine. For SPARC, a compromise is struck, with the use of pure tungsten only in the areas of highest heat flux, and a tungsten "heavy alloy" (97% tungsten, 2% nickel, and 1% iron) in areas of less intense heat flux. The tungsten heavy alloy has the advantage of being ductile and more easily machinable at room temperature; it also has a 600 MPa yield strength, whereas pure tungsten suffers from brittle fracture.

To ensure load sharing of the heat flux among the plasma-facing components, the surfaces must be machined to a tolerance of 25 µm – about one-third the thickness of the thinnest human hairs. For SPARC, the very brittle and hard-to-machine tungsten will require over 90,000 end mills. The production of these end mills is what is currently driving the plasma-facing component's critical path. Procuring all the raw materials is done or in-progress, with the first subassemblies coming together at the SPARC facility in April 2024. In total, there are 17,800 individual pure tungsten parts together weighing 6,780 kg, and there are 8,300 tungsten heavy alloy parts together weighing 10,170 kg.

Vacuum vessel

Two primary purposes of the SPARC vacuum vessel are to: (1) provide the clean vacuum environment needed to produce fusion-grade plasmas; and (2) support all internal components. While the former is absolutely necessary to get to fusion conditions, the latter poses the largest engineering challenges for the vacuum vessel.

Fusion-grade plasmas need to be very clean. There are two main problems with impurities in plasma: (1) they dilute the fusion fuel which directly reduces the reactions that generate fusion power; and (2) heavier impurities with bound electrons radiate power, which cools the plasma and reduces its performance. Lower mass impurities, like beryllium in ITER (a multi-national fusion collaboration), can be up to ~1% of the plasma number density, and higher mass impurities, like tungsten in SPARC or ITER, must be limited to ~0.001% of the plasma number density. Vacuum systems thus must have a cleanliness comparable to that of the modern semiconductor industry. The vacuum vessel is heated to 350°C before operation to eliminate gases dissolved in the steel which would otherwise slowly leak out during plasma operations and contaminate the fusion fuel. Large vacuum pumps are attached to the vacuum vessel to pump it down from atmospheric pressure and remove any gases that arise from small leaks in the ambient environment.

The vacuum vessel design for SPARC is defined by a variety of forces. These forces determine the major design aspects of the vacuum vessel, including wall thickness and the strength of connecting structures. Supporting the loads within the vacuum vessel is at the same level of difficulty as the superconducting magnets for SPARC. While the gravity loads of the vacuum vessel and internal components, as well as the load of atmospheric pressure on the outside of the vacuum vessel, are large, they are not the driving load cases for design. The plasma in tokamaks must carry a large current to maintain confinement, ~8 MA in SPARC, 200 times the current in an average arc furnace. If control of the plasma is lost, the plasma current rapidly decays and induces very large forces in all electrically conducting structures, including ~37 MN (about the thrust of the Saturn V rocket at takeoff) total vertical force on the vessel, half of which is transferred through the plasma-facing components, and ~55 MN total radial force reacted as a hoop stress in the vacuum vessel.

The SPARC vacuum vessel is manufactured with Nitronic 50, a very high-strength stainless steel. The vessel's shape conforms closely around the plasma while fitting within the toroidal field magnets. Its outer diameter is 5.7 m, its inner diameter 2.2 m, and it is 3.5 m tall, not including the port extensions, and it weighs 170,000 kg (about the weight of a blue whale). The double-wall construction features an interstitial space that serves as a channel for flowing helium gas, which heats to 350 °C before operation and removes the deposited fusion power during operation. Many systems, including radio frequency (RF) heating, as well as plasma measurement diagnostics, require access from outside the vacuum vessel. The 50 metal-sealed port flanges around the vessel facilitate these penetrations. The numerous threaded blocks and studs welded to the vacuum vessel's interior surface serve as mounts for these supporting systems.

The key to the vacuum vessel fabrication strategy was to achieve the highest level of precision that is economically feasible, along with corrective measures at subsequent stages. Adding a variety of attachment features to the vessel's construction improves the accuracy of fitting its internal parts. The cylindrical and conical sections of the vessel undergo precise shaping before assembly to ensure proper installation of internal components. The assembly involves splitting the vessel to insert the toroidal field magnets, then rejoining and resealing it. At CFS and ahead of SPARC assembly, a full-scale 60-degree mockup of the vacuum vessel, as shown in Figure 1, is used to test the fit of these internal components.

Figure 1: Full-scale 60-degree mockup of SPARC vacuum vessel at the CFS facility used for testing internal components.

Magnets

Superconducting tape holds the plasma in SPARC together, but it comes at a cost. The electromagnets making up SPARC generate very large forces within and between the magnets. The total centering force on the toroidal field magnets, which provide the confining force for the plasma, is ~3 GN, which is nearly the weight of the Empire State Building or the thrust of over 200 of SpaceX's Starships. The superconducting tape, a thin and brittle ceramic, is unable to withstand those immense loads on its own. The superconductors need robust, high-strength metal alloy structures to withstand them.

This is especially challenging because, under the cryogenic conditions (8 to 20K) in which the superconductors operate, many materials become more brittle. Thus, the alloys must be carefully selected and tested to confirm performance in these cold conditions. XM19 and 316LN are used in the SPARC magnet structures due to their high yield strength (1,150 MPa and 900 MPa, respectively), ductility (10% and 15%), and fracture toughness (140 and 200 MPa*m½) at 4K, as well as manufacturability.

There is precedent for making superconducting magnets, especially for the MRI industry, but high-field, high-temperature superconductor (HTS) magnets have never been made at the scale or performance needed for fusion. CFS has had to develop its own HTS magnet manufacturing facility at its Devens campus, with a focus on doing so in a commercially relevant way. CFS is making the first of 18 magnets for the largest magnet system for SPARC: the toroidal field magnets. Each of these magnets is composed of multiple "pancakes" (layers) of XM19 into which the superconducting tape is wound and soldered. The pancakes are stacked and assembled into a 4.4 m tall, 3.0 m wide, and 0.44 m thick 316LN case (Figure 2) and welded shut. The weight of each magnet is 19,720 kg. Each individual pancake and assembled magnet are tested in liquid nitrogen at 77K to ensure the superconducting performance of the magnets and to validate the manufacturing steps. All the pancakes for the first magnet passed this test, and the integrated first coil test is expected in mid-2024.

Figure 2: Portions of a toroidal field magnet structural case in a welding fixture.

In addition to the toroidal field magnets, SPARC will have other magnet systems – the poloidal field coils and central solenoid coils – used for controlling the plasma shape and position as well as driving the current in the plasma. These magnets, unlike the low voltage DC toroidal field coils, need to ramp quickly (up to ~4 T/s) and withstand high terminal voltages (>1 kV). Such magnets are more amenable to a cable-based design where the HTS is wrapped in its own structural steel jacket and then overwrapped in insulation to withstand the high voltages, much like the same magnet systems in the larger, lower field ITER tokamak. CFS' internal manufacturing line for its insulated, cable-based HTS magnets is up and running, producing the first poloidal field coil for SPARC.

Cryostat and thermal shield

The cryostat enables the superconducting magnets to remain cold (8 to 20K) and superconducting. The cryostat, acting like a thermos, reduces the heat transfer from both the ambient environment and the vacuum vessel to the superconducting magnets, significantly reducing the cryoplant's cooling power demands. This is accomplished by three main mechanisms: (1) The cryostat maintains a vacuum (10^{-4} Pa or 10^{-9} atmospheres), removing air from the space around the magnets and eliminating the heat that would've been conducted through it; (2) The cryostat and magnet surfaces have low emissivity to reduce radiated heat transfer; and (3) There is an intermediate thermal shield cooled with gaseous helium (80K) to further reduce the radiated thermal loads on the superconducting magnets.

The cryostat, encompassing the entire tokamak, serves as the "face" of the machine when assembled. It comprises some of the largest parts of the machine, with a diameter of 9.7 m, a height of 10.7 m, and a total weight of 175,000 kg, nearly the same as the SPARC vacuum vessel. The cryostat's base, shown in Figure 3, is currently being manufactured in Italy and will be installed as the first component of the machine in late 2024.

Figure 3: First portion of the SPARC cryostat base weldment. The various holes are for connections to systems within the cryostat including electrical and cooling for the superconducting magnets.

Motor-generator and power conversion equipment

The SPARC poloidal field and central solenoid coils require a large pulsed power to ramp up and down for the SPARC plasma pulse. A fusion facility has two main options for obtaining the necessary power: (1) directly from the electric grid, or (2) through energy storage in a flywheel. The latter was found to be the best choice for SPARC due to its simplicity for interfacing with the local electric grid. The system consists of three major components: (1) a motor generator, (2) a flywheel, and (3) power conversion equipment.

A motor generator is essentially a very large electrical motor used for converting between electrical and mechanical energy. Constellation Energy donated the generator for SPAC instead of purchasing a new one. It is a recently retired generator that supplied electricity to the

Boston area for nearly 50 years at the Mystic Generating Station in Everett, MA (Figure 4). Two 90,000 kg flywheels are added to the 54,000 kg motor generator rotor to increase the rotating mass and potential for energy storage. With a peak rotational velocity of 3,600 rpm, the total stored energy is 4.7 GJ (equivalent to the battery storage capacity of ~10 Cybertrucks), of which 2.1 GJ is usable for the SPARC pulses due to the limited frequency range of the power conversion equipment. It takes around an hour to slowly spin the system up, adding energy from the grid. The system will operate with up to 400 MW of real and 1000 MVA of reactive powers to supply energy to the pulsed magnets.

The AC power output by the motor generator must be converted into the currents and voltages needed for each individual magnet to operate. GE conversion equipment, typical of large-scale arc furnaces and electrolyzers, operates up to approximately ±2.5 kV and ±50 kA in 18 thyristor rectifier power supplies. A fast response for the vertical stability coil will be implemented with a ±1kV, ±30kA IGBT (insulated-gate bipolar transistor) power supply.

Figure 4: Stator from the Constellation Energy Mystic Generating Station on a temporary storage stand at the SPARC site. The stator will soon be installed in the energy storage building along with the rotor and flywheels.

RF plant

The fusion plasma needs to be heated with an external system to get to the ~100 million °C optimal for fusion energy production. While many options exist for such a system, ion-cyclotron resonance heating (ICRH) was chosen for SPARC due to its proven physics and engineering in other high magnetic field tokamaks (Alcator C-Mod), its ability to heat deuterium-tritium fuels in tokamaks (JET and TFTR), as well as its relatively low cost per unit power due to its use in commercial applications. The ICRH heats the plasma by coupling RF power through an array of antennas a few centimeters outside of the plasma. The RF waves propagate into the plasma until they hit a resonance with the plasma ions gyrating in the magnetic field and transfer the RF energy into the kinetic motion of the ions, increasing the plasma temperature to fusion-relevant levels (10-20 keV or 100-200 million °C).

Supplying the ICRH antennas in SPARC is one of the largest and most advanced very high frequency (VHF) RF systems ever fielded. The high magnetic field in SPARC (12.2 T at the plasma center) results in an ICRH frequency of 120 MHz with a +/- 1 MHz bandwidth; this is just above the band in which FM radio operates (87.5 to 108.0 MHz). Previous generations of ICRH systems used large-scale (~2 MW) vacuum tubes to supply the RF power needed to heat the plasma. While effective enough for many fusion experiments, the century-old technology had low efficiency, was prone to failure, and is becoming largely obsolete with little new demand for commercial production. Solid-state amplifiers are now available in sufficient performance, quantity, and price to justify their use in the SPARC ICRH system and fusion power plants beyond.

In the SPARC system, there are 360 solid-state amplifiers per transmitter, each with a 6 kW maximum output (equivalent to about six household microwave ovens), arranged around a 2 m diameter, 1.2 m tall cylindrical combining cavity. The system is water-cooled and supplied by DC-DC converters, regulating the 65 VDC supply voltage. Energy is stored for each 10-second plasma pulse in a super capacitor system with 22 super capacitor banks, each at 176 F up to 816 V, with a maximum total energy of 1.29 GJ. The total RF source power is 46.2 MW.

Each combining cavity is connected to the antennas through a 30 Ω coax with a 155 mm-diameter copper center conductor and a 266 mm aluminum outer conductor (Figure 5). The average path length from transmitter to antenna is ~56 m. Inside the tokamak vacuum vessel, there are 14 total antennas, each composed of four transmitting straps. The end-to-end system efficiency of this novel solid-state ICRH system in converting electricity into RF power into the plasma is >70%; a vacuum tube-based system would be 50% efficient at best. The system couples up to 25 MW of RF power into the plasma in total. In comparison, FM radio stations in the U.S. are now limited to 0.1 MW transmission power. If the SPARC ICRH was an FM station, it could transmit farther than a high-power U.S. station.

The ICRH system is well along the way to being ready for first operations; the first transmitter is 90% procured, with only DC-DC converters still to come in. All major components have been prototyped at scale and confirmed to meet specifications. The team anticipates that the first full transmitter will be assembled and tested in the third quarter of 2024, and 10 more transmitters will be installed by the end of 2025. Half of the 1,600 m of coax transmission lines are already installed between the transmitters and the tokamak hall, with the remainder installed by the end of the third quarter of 2024.

Cryogenic cooling

Even though SPARC uses "high temperature" superconductors, they still require cryogenic cooling to allow the magnets to function at high fields. A large helium cryogenic system similar to other large superconducting facilities like the European Spallation Source (ESS), accomplishes this, albeit with additional unique challenges.

Steel is Real: Making Concrete Progress to Fusion Energy

Feature

The SPARC cryogenic cooling system is composed of the cryoplant and cryodistribution subsystems. The cryodistribution system supplies cryogenic helium from the cryoplant to the SPARC tokamak at three temperature levels (80K, 15K, and 8K), removing heat from the superconducting magnets, thermal shields, and other users before returning the helium to the cryoplant. The cryoplant then rejects this heat into the SPARC cooling water system. Heat removal amounts at the three temperature levels vary widely during SPARC operation, from cooldown through fusion pulses. One of the SPARC cryogenic system's unique challenges is accommodating over 15 different operating modes.

Figure 5: RF coax installed at the SPARC facility for transmitting the RF power from the plant to the plasma

The cryoplant is a three-stage Brayton cooling cycle that includes liquid nitrogen pre-cooling. It has a steady-state heat removal capacity of approximately 30 kW at 10K. Two 12 m long by 4 m diameter screw compressors dominate the plant's 4MW power consumption. The compressors have been manufactured, tested, and are being installed on the SPARC site (Figure 6). The working fluid of the cryoplant is supercritical helium, and heat removal requirements can vary rapidly in time. Another unique challenge of the SPARC cryogenic system is maintaining the plant's temperature stability under highly transient conditions.

Since SPARC is an experimental device and not a complete fusion power plant, its design is "sub-shielded." That is, in a fusion power plant, there will be a significant amount of shielding around the superconducting magnets to reduce neutron damage and ensure that the magnets have a multi-decade lifetime. Reduced shielding means increased power deposition in the superconducting magnets, with peak heat fluxes of ~1 MW/m^3. Without active cooling, the temperature of the superconducting magnets would quickly rise beyond their limits. While the cryoplant can handle most of the cryogenic heat loads in SPARC, it is unable to keep up with the largest fusion power pulses. To handle these pulses, the SPARC cryogenic distribution system has an additional feature; the SPARC blowdown system. The system consists of a series of 20 m tall, 3 m diameter "blowdown" tanks that propel, supply, recover, and receive 240 kg/s of stored 8K helium to keep the toroidal field magnets cool. The system is capable of transient heat removal at 3 MW for 10 seconds. The unique challenges here are the demanding requirements and novelty of the integration; this system functions effectively as a supercritical helium rocket test stand that is resettable.

Figure 6: Cryoplant main compressors and oil removal system installation in the SPARC Utility Building.

Summary

The CFS team, along with its collaborators and vendors, is well on its way to building SPARC to demonstrate commercially relevant net energy from fusion for the first time in world history. The climate crisis is well researched, documented, and debated. Equally, the debate over fusion being the "Holy Grail" of carbon-free energy has a long history of proponents and detractors, even to this day. CFS is solving the world's greatest challenge with a solution that scales to the size of the problem: commercial fusion. Their team is able to do so within a privately held, for-profit enterprise because of the unique innovations described above. As Bill Gates (full disclosure: a CFS investor) recently told an audience of oil and gas executives, "In the long run, fusion will be almost certainly the primary source of electricity on the planet" [2]. CFS is paving the way for fusion to be the cornerstone technology for the urgent global transition to carbon-free energy sources.

Dan Brunner co-founded CFS and serves as Chief Technology Officer. He owns the company's technology roadmap and intellectual property management, ensuring the team is developing and delivering the technology needed to field economic fusion energy. In the early days at CFS, Brunner built and led both the SPARC and WHAM teams, the former with nearly 50 scientists and engineers, through to their conceptual designs.

As an MIT research scientist and a Ph.D. student at MIT's Plasma Science and Fusion Center, Brunner's specialization and contributions in systems that mitigate the immense heat fluxes in fusion devices, and the development of the most compact plasma probe gave him great experience in complicated high-end engineering and system designs.

Brunner holds a Ph.D. in applied plasma physics from MIT, and a B.S. in engineering physics from the Rose-Hulman Institute of Technology.

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The Chapter Support Initiative: Going Strong in Year Three

The launch of the IEEE-HKN Chapter Support Fund in 2022 was established to create new and enhance existing resources, training, and programs to help every Chapter thrive. A strong Chapter, in turn, helps ensure that members have a fulfilling HKN experience throughout their entire careers. The two facets of this fund include the IEEE-HKN Student Chapter Support Grant program and a supplemental Chapter support program. Things are going quite well as we start the third year of this initiative!

One aspect of the Chapter Support Program includes onboarding newly installed university Chapters. HKN welcomed four new Chapters into the community in the first few months of 2024!

In February, IEEE-HKN Past-President, Sampathkumar Veeraraghavan, traveled to install HKN's first Chapter in Ecuador at the Escuela Superior Politécnica del Litoral (ESPOL). Thirteen students and one professional member were inducted as Charter members of the Nu Zeta Chapter. ESPOL's rector, Cecilia Paredes, was happy with the installation of this Chapter. "We are all aware of the benefits it will mean for all engineering careers, the university, and most importantly, for the students themselves," she said.

Nu Zeta Charter Members

The month of March brought two more university Chapters into the HKN family: Nu Iota Chapter at Óbuda University and Mu Gamma Chapter at the Polytechnic University of Puerto Rico! IEEE-HKN President Ryan Bales traveled to Budapest to install Nu Iota Chapter and induct 21 charter members. IEEE-HKN President-Elect, Sean Bentley, traveled to San Juan to install the second Puerto Rican Chapter and induct 16 new members there.

Mu Gamma Charter Members

In April, we expanded our presence in the southern U.S. when 2022 IEEE-HKN President Jim Conrad installed the Lambda Chi Chapter at Hampton University in Virginia, welcoming 11 charter members into HKN.

The momentum surrounding this growth shows no signs of slowing. We look forward to installing a Chapter at Texas State University later this year. Eight more universities around the globe have been approved to petition the IEEE-HKN Board of Governors to form new Chapters and we look forward to seeing those efforts come to fruition.

Along with new-Chapter-onboarding, HKN is working with universities to reinstate inactive and dormant Chapters to help them resume operations. Students and faculty from four universities with long-dormant HKN Chapters are working to reactivate: Michigan State University, University of Michigan-Dearborn, Bradley University, and Montana State University-Bozeman. The Iota Kappa Chapter at MSU Bozeman started with the process in January and has already held two induction ceremonies since.

HKN Board members, volunteers, and staff continue to work with Chapters that initiated coaching relationships in 2022 and 2023 as well, providing guidance and support with things like reporting, officer transition, recruitment, and more.

Impactful Grant-Funded Activities

The Chapter Support Grant Program is on track to match its 2023 success! Chapters across the world are planning and executing innovative, community-building programming made possible by these grants. Lambda Omicron Chapter at Miami University, Nu Eta Chapter at Sri Sairam College of Engineering, Nu Theta Chapter at Purdue University Northwest, Xi Chapter at Auburn University, and Mu Beta Chapter at Arab Academy for Science & Tech - Alexandria received grant funds to host STEM-outreach events in their communities.

Twelve grant applications have been submitted in 2024 so far. Stay tuned for more information about all the things our Chapters are doing with help from this initiative.

About the Chapter Support Initiative

John McDonald, Beta Chapter, and his wife, Jo-Ann, made the first gift to this dedicated fund that provided the mechanism to launch the program. Please join with them in the mission to give every student the chance to be part of a successful Chapter. You can make a contribution here by choosing the Student Chapter Support Fund from the dropdown menu. If you would like to hold a confidential discussion about your gift, please contact us.

IEEE-HKN Celebrates its Outstanding Chapters and Student at the 2024 ECEDHA Conference

On 14-17 March, representatives from IEEE-HKN attended the annual Electrical and Computer Engineering Department Heads Association (ECEDHA) annual conference held in Tuscon, Arizona, to network and celebrate the achievements of its members. A special awards ceremony was held on 17 March to recognize HKN's Outstanding Chapters and bestow the Outstanding Student Award.

Outstanding Chapter Award

The prestigious Outstanding Chapter Award is presented to IEEE-HKN Chapters in recognition of excellence in their Chapter administration and programs. Just 21 Chapters out of 273 were recognized for their work during the 2022-2023 academic year.

Ryan Bales, 2024 IEEE-HKN President, S. K. Ramesh, Lambda Beta Chapter Advisor, and Tom Coughlin, 2024 IEEE President

Chapters are selected based on their activities, community service and outreach, and the impact they have had on their department, university, and the community. Of vital concern to the Outstanding Chapter Awards evaluation committee are activities that advance professional development, raise instructional and institutional standards, encourage scholarship and creativity, provide a public service, and generally further the established goals of IEEE-HKN. In 2023, HKN Chapters performed close to 110,000 hours of activities, of which 46,000 were dedicated to service/education and outreach.

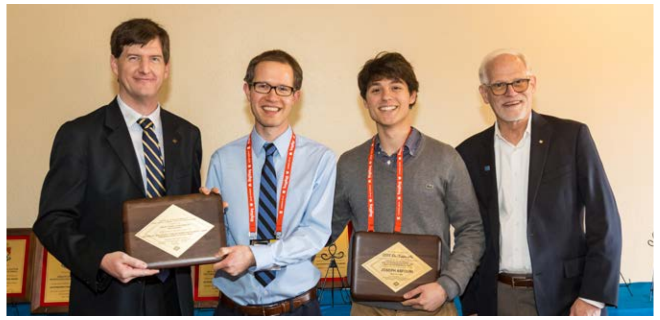
The 2022-2023 Outstanding Chapter Award Recipients are:

Outstanding Chapter Award winners displaying their awards.

Beta	Purdue University
Epsilon	Pennsylvania State University
Mu	University of California, Berkeley
Beta Delta	University of Pittsburgh
Beta Epsilon	University of Michigan
Beta Eta	North Carolina State University
Beta Mu	Georgia Institute of Technology
Gamma Beta	Northeastern University
Gamma Theta	Missouri University of Science and Technology
Delta Omega	University of Hawaii, Manoa
Epsilon Sigma	University of Florida
Kappa Omicron	State University of New York, New Paltz
Kappa Psi	University of California, San Diego
Lambda Beta	California State University, Northridge
Lambda Zeta	University of North Texas
Lambda Tau	University of Puerto Rico, Mayaguez
Mu Alpha	UCSI University - Kuala Lumpur
Mu Beta	Arab Academy for Science & Tech - Alexandria
Mu Mu	Wentworth Institute of Technology
Mu Nu	Politecnico Di Torino
Nu Gamma	The College of New Jersey

Outstanding Student Award

Joseph Asfouri from the Theta Rho Chapter received accolades for being selected as this year's winner of the Alton B. Zerby and Carl T. Koerner Outstanding Electrical or Computer Engineering Student Outstanding Student Award (OSA). Each year, the Los Angeles Alumni Chapter of IEEE-HKN solicits nominations and selects a recipient for this prestigious award. Joseph says, "The Outstanding Student Award is a great honor for me personally, but I'm even prouder of the recognition it gives my alma mater, Rice. I simply took advantage of the generous opportunities and collaborative environment cultivated by Rice's faculty, staff, and students, particularly those in the ECE Department. It was my professors and mentors at Rice who inspired and facilitated my achievements in academics, neuro-engineering research, and service to K-12 FIRST® Robotics teams over my four years there. These achievements were truly a team effort, and the award goes to this team as much as it goes to me. Thank you to the selection committee and the Los Angeles Area Alumni Chapter for this recognition!" You can learn more about Joseph Asfouri in the HKN Student Profile.



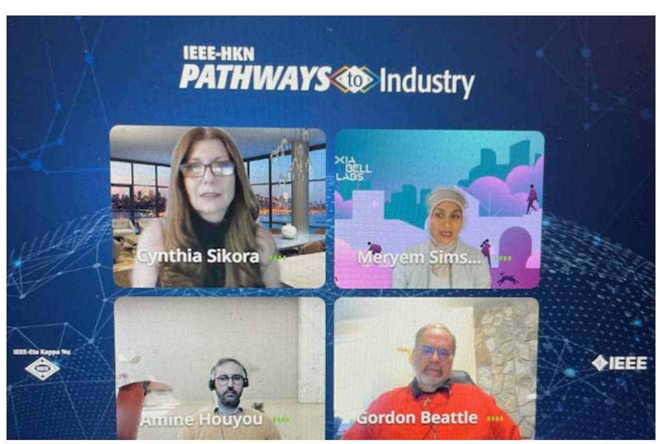
left to right: Ryan Bales, 2024 IEEE-HKN President, Joseph Cavallaro, Theta Rho Chapter Advisor, Joseph Asfouri, Outstanding Student Award winner, and Tom Coughlin, 2024 IEEE President

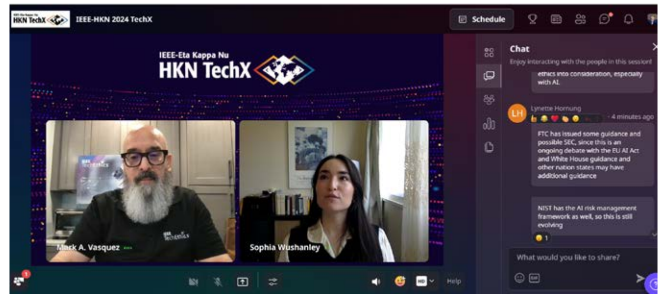
Congratulations also to the other finalists: Jeremy Lee Sze Ern, Lambda Omega Chapter, National University of Singapore; Leslie Miller, Epsilon Beta Chapter, Arizona State University; and Binh Tran, Theta Phi Chapter, Virgina Military Institute.

HKN's Virtual Conferences offered Students and Young Professionals the Opportunity to Learn from Industry and IEEE Society Professionals

Along with the annual Student Leadership Conference held in person each fall, HKN sponsors two virtual conferences, Pathways to Industry and HKN TechX, which are open to all with the goal of sharpening career readiness skills for students and young professionals. Held on 21-23 February 2024, the ***HKN Pathways to Industry*** virtual conference focused on topics such as career opportunities at the National Laboratories and those created by the CHIPS Act, interview tips, how to leverage continuing education and IEEE Society membership to get a leg up, etc. World-wide attendance topped 300 and offered attendees nine learning sessions, three networking opportunities, and two keynote speakers. One highlight of the conference was the X-Factor Conversation with HKN Eminent Member, Dr. Bob Kahn, led by 2019 HKN President, Dr. Karen Panetta, where he shared what it was like to be one of the Internet's earliest innovators. The new virtual conference platform, Airmeet, allowed for easy networking among attendees and HKN Board members and volunteers who offered one-on-one resume and career advice. In addition, there were two dedicated recruitment fairs where attendees could visit virtual booths and meet with recruiters to learn of current internship and job opportunities. One attendee relayed the value he received, stating, "*The Pathways to Industry* virtual conference offered a unique blend of technical information sessions and personalized meet-and-greet opportunities. Attendees not only gained valuable professional insights but also had the chance to engage on a personal level. It was a refreshing and enriching experience overall."

HKN TechX followed on 17-19 April which explored the theme of "Ethical Considerations of New Technology." Matthew Jackson, chair of the 2024 TechX subcommittee





and Epsilon Beta Chapter alum, described the value of the conference as follows, "Throughout the conference, we had many important conversations with thought leaders from industry, academia, and IEEE technologies surrounding how tech ethics is integrated with their careers and the impact it can have on research, industry, and our communities. A highlight was hearing our panelists speak to students and professionals on where tech ethics meets today's fastest growing fields and the skills they can acquire to stand out in the job market, for example, assuring accountability in artificial intelligence." Attendees were treated to keynote addresses by Dr. Karen Panetta, who shared her groundbreaking work in AI; Fred Schindler, VP of IEEE Technical Activities, who advised on how to find one's technical "home;" and Dr. Sandy Magnus, HKN Eminent Member and former NASA astronaut, who regaled her time on the International Space Station and encouraged participants to follow their dreams. Attended by 264 participants from around the world, the conference included nine additional learning sessions, three networking sessions, and two recruitment fairs where our 12 sponsors received over a thousand visits to their booths.

According to Christian Winingar, Gamma Theta Chapter alumnus and assistant distribution engineer at Burns & McDonell, "I have had the amazing opportunity to listen to multiple panels and technical discussions at IEEE-Eta Kappa Nu TechX. I was thankful to be able to network with and learn from so many different industry professionals. This was my second year attending TechX, and I am constantly amazed at the amount of information I can gain from an online conference."

An advantage of virtual conferences is that sessions are recorded and can be accessed for later viewing. Sessions from past Pathways to Industry and TechX conferences are available on the HKN YouTube channel. Watch for 2024 conference sessions to be released on YouTube this summer.

Fusion Ignition and the Path to Inertial Fusion Energy continued from page 14

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HKN features an Alumni Reception, a Professional Induction, and the Best Student Paper Award at SouthEastCon!

This year's SouthEastCon was filled with scholarship, character, and attitude with HKN members leveraging the convening to connect and induct new members. Held on 20-24 March in Atlanta, Georgia, SouthEastCon provided a perfect venue for HKN alumni to gather and network, and, of course, have some of the increasingly famous, HKN cake. HKN 2024 President Ryan Bales presided over the induction of three professional members into the Eta Chapter—Masood Ejaz, Professor Arup Kumar Ghosh, and Brian Page.

New Eta Chapter members taking their HKN pledge.

Alireza Marefat, a Ph.D. student at Georgia State University, was this year's winner of the IEEE-HKN Best Paper Award presented on 25 March 2024, for his paper entitled, "A Framework for Classifying Applications from Raw Network Traffic Traces." The IEEE-HKN Best Student Paper Award is presented annually at SouthEastCon. The primary and presenting author must be a student. Of the seven papers submitted, four finalists were selected. Each author presented their paper to a panel of judges. Regarding this award for his work, Marefat states, "Winning this recognition means a lot to me, but the connections I've made are truly invaluable." For his achievement, Marefat will receive a check for $500. The IEEE-Eta Kappa Nu Best Student Paper Award was established by a generous donation by Dr. Hulya Kirkici and the IEEE Power Modulator Conference.

Here is an abstract of the winning paper:

In this paper, we study and present the design of a framework to identify applications from raw network traces. Framing the problem as an application classification problem, we set up the framework to extract key features from packet data and their temporal behavior. The feature generation, their training using traditional machine learning models, and the decision-making are executed over a four-stage pipeline, to yield the name of the application. Through an in-lab environment experimentation using the OpenWrt toolkit, RaspberryPi, and a set of physical devices (generating network traffic), we evaluated on average about 204K data points from the captured network packet traces for six applications. Our results show that our method is able to classify the applications with at least 90% accuracy. Through micro-benchmarking, we also show the feasibility of scaling the number of applications and running the tool in real time.

left to right: Eric Grigorian (IEEE Region 3 Director), James Conrad, (2022 IEEE-HKN President), Alireza Marefat (Best Student Paper winner), and Nelson Lourenco (Region 3 Awards Chair)

We are already ready looking forward to the next SouthEastCon to be held 27-30 March 2025 in Charlotte, NC!

Kappa Psi Middle School Outreach Program

Kappa Psi's dedicated outreach team conducts dynamic elective classes tailored for computer science, electrical engineering, and mechanical engineering undergraduates. In these hands-on courses, students develop lessons on engineering topics they are passionate about, learn how to effectively teach by conducting dry runs and receiving feedback, and then present these lessons at underserved K-12 schools all across San Diego County.

In an effort to further excite the youth while introducing engineering, our outreach team recently expanded to hosting on-campus outreach tours. What better way to excite students than to go on a field trip? Students witness college life firsthand at the University of California, San Diego (UCSD), touring the campus and various graduate engineering laboratories dedicated to solving real-world challenges. Students receive captivating demos that showcase the impactful projects these labs are spearheading. After touring the labs and UCSD's landmarks, the students end the day off enjoying food, interacting with college students, and running around with their classmates on Sun God Lawn. Allowing students to enjoy the day while leaving a positive impression of college life and presenting captivating engineering initiatives might lead students to desire to become engineers and potentially make waves within the world.

The students taking a picture at Geisel Library.

The students receiving a demo of an autonomous healthcare robot that can perform chores and carry objects.

Celebrating the Research Contributions of Our Graduate Student Members

Graduate students, an important and growing part of the IEEE-HKN global community, are performing groundbreaking research. We have developed this award-winning section in *THE BRIDGE* to celebrate and elevate their research contributions. The HKN Graduate Student Research Spotlight is a standing feature in *THE BRIDGE*. The profiles of the students and their work will also be shared on our social media networks.

Each profile will showcase the intellectual merit and broader impact of HKN graduate student members' research and provide information about the students' backgrounds and where people can learn more about them and their work.

We will spotlight these achievements while also showing potential graduate students what is possible!

Would you like to be featured?

Fill out our submission form. Submissions will be reviewed, assembled into a profile template, and posted on HKN's social media pages. A select number of profiles will also be featured in *THE BRIDGE*.

Advertising Opportunity

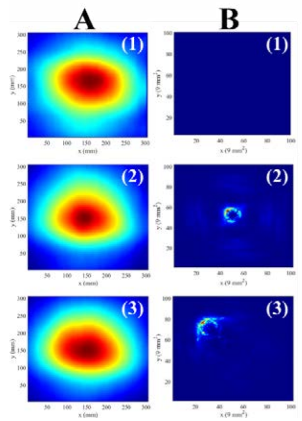
IEEE-HKN is the professional home to the world's top graduate students in electrical and computer engineering, computer science, and allied fields of interest. Get your company or university in front of these students and HKN's undergraduate students who are considering their next steps by advertising in a special section of *THE BRIDGE*. Click here for more information and rates.

Logan M. Wilcox

Gamma Theta
Missouri University of Science and Technology, Ph.D. Candidate in Electrical Engineering

RESEARCH TOPIC
Spatial-Temporal Variance Reconstruction for Thermographic Images

Active Microwave Thermography, or AMT, is a coupled electromagnetic and thermal nondestructive testing technique that utilizes an active electromagnetic source to induce thermal excitation. The resultant temperature distribution across the inspection surface is subsequently measured by an infrared camera and is, generally, nonuniform. This nonuniform heat generation is cause for concern, as a defect can be masked (i.e., false negative) or incorrectly detected (false positive) because of the nonuniformity. To this end, a novel post-processing technique has been developed to reduce the impact of the antenna pattern on measured thermal images, which utilizes the influence of a defect on the spatial and temporal components of a thermographic data set and is referred to as Spatial-Temporal Variance Reconstruction (STVR). An example of STVR can be seen in the figure, where three unprocessed (left, A) and corresponding reconstructed (right, B) images (defect-free (1), centered defect (2), and offset defect (3)) are shown. Here, on the left, the presence of a defect cannot confidently be detected in (2) and (3) due to the resemblance to (1). On the contrary, the right side provides a clear indication of the defect in (2) and (3) and no indication of the defect in (1) through the use of STVR.



Unprocessed (A) and reconstructed (B) thermographic images of defect-free (1), centered defect (2), and offset defect (3) specimens.

LEARN MORE
https://scholar.google.com/citations?user=pJCx6oYAAAAJ&hl=en

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M. Aladdin Mousa

Beta
Purdue University, Ph.D. Student in the School of Electrical and Computer Engineering

RESEARCH TOPIC
Advancing Ultrafast Highly Sensitive Thermal Imaging for Room-Temperature Operation

My research is dedicated to enhancing thermal imaging technology by addressing the challenges faced by digital-mode cameras, which typically operate at extremely low temperatures. Our breakthrough involves utilizing spintronic-based materials, making it possible to create digital-mode thermal cameras that work efficiently at room temperature.

In the design of this thermal camera, we've employed engineered materials to enable 'clicks' through thermally activated transitions between magnetization states. This innovation results in ultrafast readout speeds and exceptional thermal sensitivity tailored for room temperature thermal imaging.

The broader impact of our work is noteworthy, particularly in applications like HADAR (Heat-Assisted Detection and Ranging) for autonomous navigation. Operating at room temperature, our thermal camera addresses important challenges, achieving both high sensitivity and high-speed operation simultaneously—a significant advancement for various practical applications. This innovation not only expands technological possibilities in thermal imaging but can also bring about positive changes in diverse real-world scenarios. HADAR, which combines thermal physics, infrared imaging, and machine learning, lays the groundwork for fully passive and physics-aware machine perception in self-driving vehicles.

HADAR, or heat-assisted detection and ranging, combines thermal physics, infrared imaging and machine learning to pave the way to fully passive and physics-aware machine perception.

LEARN MORE
https://scholar.google.com/citations?user=NFQ9RXoAAAAJ&hl=en

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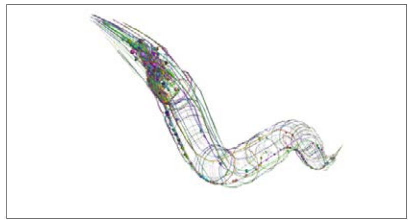
Quilee Simeon

Beta Theta
Massachusetts Institute of Technology, Interdisciplinary Ph.D. Candidate in Brain and Cognitive Sciences and Statistics

RESEARCH TOPIC
Neural Computation in C. *elegans*

My research aims to develop whole-nervous system computational models of the nematode Caenorhabditis elegans (C. elegans). This endeavor requires an interdisciplinary approach, leveraging the tractability of C. *elegans* as a model organism to understand how complex neural processing is linked to behavior. Toward the ultimate goal of reverse engineering an entire nervous system (link), I have done preliminary work investigating the scaling properties of using artificial neural networks to model neural activity in C. *elegans* (link).

My work stands at the crossroads of systems neuroscience, dynamical systems, and modern statistics (machine learning). By merging concepts from diverse fields, I am contributing to a unified framework that constructs bio-computational models by assimilating neurobiological data with engineering advances in the architecture and training of neural networks. This approach may lead to improved prediction and simulation of neural dynamics and behavior. My work is a small part of a larger quest within computational neuroscience to interpret the rich information processing and control capabilities of nervous systems.



Three-dimensional rendering of the C. elegans neural connectome, depicting the intricate wiring diagram of its nervous system, with the 'brain' of the worm located in the head (upper-left). Image attributed to the OpenWorm and VirtualWorm projects.

The potential impact of my research stretches beyond academia. Understanding neural computation in a model organism could lead to the development of adaptive AI systems with bio-inspired principles like energy efficiency. The potential of simulating an entire nervous system in silico has been a long-standing theme of science fiction, but it has real practical applications, like testing clinical interventions. The interdisciplinary work I do in my PhD is a small step towards these long-term goals, embodying the incremental and collaborative nature of scientific progress.

LEARN MORE
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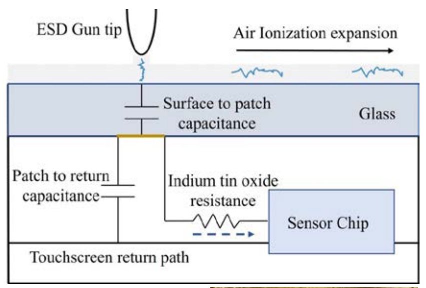
Zhekun Peng

Gamma Theta
Missouri University of Science and Technology, Ph.D. Student in Electrical Engineering

RESEARCH TOPIC
Modeling of Air Discharge on Touchscreen Surface

Electrostatic Discharge (ESD) in touchscreen displays can result in device failures. A human handling an electronic device can cause air discharge to the touchscreen. Due to the high impedance and dielectric breakdown strength of glass, the discharge does not cause a spark but instead creates an ionized corona and keeps expansion on the glass surface. Significant energy can be coupled to the sensor chips under the screen through the displacement current and cause soft and hard failures. Models for the corona discharge to touchscreens could allow designers to evaluate ESD robustness at the pre-compliance level.

The air discharge test is well known for its bad repeatability. An automated measurement setup is designed for better control over the unintentional influencing factors such as humidity, temperature, discharge position, and approaching speed. Lichtenburg dust figure helps to visualize the invisible charge that remains on the glass surface after a corona discharge. The geometry of the dust figure guides the analysis of current distribution at different distances from the discharge center. The model shows a good correlation between the total discharge current, the ionized air resistance, and the displacement current to each sensor patch. Additional work is planned on the transient and current- dependent model of the single streamer to predict the air discharge current without any measurement.



Above: Schematic illustration of a cross-section for air discharge to touchscreen surface.
Right: Example of dust figure on touchscreen surface

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Joseph Asfouri

University of Cambridge, MPhil in Biotechnology, Theta Rho, Rice University

> He predicts that "the democratization of these AI tools will make coding and designing easier to learn and do, **improving diversity among engineers and allowing them to start innovating even earlier in their lives.** This is an extremely exciting prospect for society globally."

Joseph graduated in May 2023 from Rice University, where he majored in electrical engineering and neuroscience. Fascinated by the intersection of these two fields, he has worked on developing genetically targeted neural stimulation with magnetic fields (Rice University), discovering the neural basis of mood with closed-loop deep brain stimulation (Baylor College of Medicine), and investigating the role of visual feedback in brain-computer interface learning (University of Washington). Beyond engineering therapies for neurological and neuropsychiatric diseases, his interests include science policy and commercialization to translate these innovations safely and efficiently from the lab to the clinic.

As this year's winner of the Alton B. Zerby and Carl T. Koerner Outstanding Student Award, Joseph Asfouri embodies HKN's commitment to scholarship, character, and attitude. As an undergraduate student, Joseph started the university club *FIRST*® at Rice, which supports underserved K-12 *FIRST*® Robotics teams throughout East Texas with mentorship from Rice students and funding from Houston tech companies. This year, he is studying on a Churchill Scholarship for a master's degree at the University of Cambridge, where he is working to develop a bioelectronic implant to enhance regenerative stem cell therapy for Parkinson's disease. This fall, he will start his Ph.D. in the UC Berkeley-UCSF Joint Bioengineering Program, furthering his goal of becoming an academic professor and leading a neuroengineering lab.

Joseph realized that he loved engineering in his sophomore and junior electrical engineering classes at Rice, when his professors demonstrated that by intuitively understanding just a few fundamental concepts, the most complicated architectures or algorithms are put within reach. According to Joseph, the other thing that he loves about engineering is, "its consequences and implications, particularly those posed by AI, for all other fields of human knowledge. Innovation uproots existing axioms that other disciplines hold about society, and I think studying and addressing the implications of innovation provides an exciting opportunity to bridge intellectual divides between STEM and the humanities and social sciences."

Always looking towards the future, Joseph is excited by the future challenges and opportunities to the field posed by AI's semi-automation of coding and other computer-aided processes that will significantly accelerate innovation among current engineers. He predicts that "the democratization of these AI tools will make coding and designing easier to learn and do, improving diversity among engineers and allowing them to start innovating even earlier in their lives. This is an extremely exciting prospect for society globally." However, he cautions that "the democratization of such powerful tools carries vast consequences, and perhaps the most concerning is the generation of fake content for malicious purposes. I think it is absolutely critical that as AI tools get better and more widespread, tools for quickly and accurately detecting AI-generated content get better even faster." He thinks this may be one of the greatest engineering challenges of our time.

The advice that Joseph gives to his fellow students is, "First, identify a major social problem that you want to dedicate your career to solving. Thinking back on this problem will keep you motivated throughout the toughest parts of college. Second, try to take many proof-based math courses early on, as they will build up your logical reasoning (especially useful for scientific research) and give you intuitions on math concepts that will help immensely in your engineering classes." Another piece of advice that Joseph gives is to start doing research as early as possible, stating, "The first semester of freshman year is not too early! Starting early is challenging but will pay off in your research skills and your relationships with mentors and professors, which both take a long time to build."

When asked to finish the sentence, "If I had more time, I would …," he replied, "upload my consciousness so I could have even more time." With character, attitude, and scholarship like that, it is no wonder that he is this year's Outstanding Student Award winner!

Jim Jefferies

Beta Psi Chapter

New HKN Board Member Jim Jefferies Reflects on his Career and the Future

Inspired to become an engineer by the "Sputnik scare" and his engineer father, Jim Jefferies has long appreciated the continuous opportunity to learn and apply knowledge that the field of engineering provides. Like so many successful engineers, he remembers "visits to the 'electronics store,' disassembling electronic items," and even helping his father grade tests as he taught a basic electronics class at Omaha University. He served as President of the Engineers Club of Omaha soon after his graduation as a first-generation college student, stating, "My march into the profession was a very direct and uninterrupted path."

Over the course of his long and successful career at AT&T, he took great satisfaction in being able to understand, design process, and produce a quality product to meet a need, even seeing a product of his work at an exhibit on telecommunications history at the Smithsonian Museum, recounting, "I saw on display one of the last versions of a mechanical crossbar switch that I had been the manufacturing engineer for. I did think they were a little premature in putting it in the museum. "

Since he has entered the profession after receiving a generalized education, Jefferies feels that the field has become more diverse, more complex, and more specialized, "for example, understanding the single transistor circuit and logic gate as opposed to a billion-transistor chip, a computer design at the shift register and machine language level, or programming on punch cards and tapes." But this complexity offers additional opportunities for collaboration and increases the value of mentorship. He recalls, "An early experience for me was studying for a professional engineering license with IEEE members who had more experience in the other specialties." Furthermore, he states that "it is important to respect and recognize the contribution of every individual. When you see that happening, you know they will be on a successful team and are on the path to fulfillment."

Jefferies predicts that over the next 10 years collaboration will become even more important as solving large problems will necessitate diverse teams of individuals bringing in specialized knowledge. With the pace of technological innovations, he sees continuing education as a growing need. In addition to the pace, he was concerned with the "power" of technology, advising that "it will also become increasingly important to understand the implications and impact of technology on society and the ethics surrounding that power." He challenges us to think about the question, "Can we effectively harness the spectacular expansion while not manipulating, creating equity imbalances, or even abusing the user?" before rushing to implementation.

Despite his predictions, one lesson that he has learned during his time in the field is that the "future is not certain and needs to be explored, created, and managed in a developing context." He advises young engineers to be open: "Every promotion or major opportunity that happened in my career had an element of surprise or was opened up by major and unpredictable changes way beyond my ability to foresee or control." Jefferies also advises HKN students and young professionals to do the following:

> "Do the best you can to understand where you or your skills fit and contribute, take some time to understand the broader organization if a large company, the needs of the business in a smaller company, or just seeing people in related fields or departments. **Seek learning opportunities** without judging their value or worth too much and recognize that more people are watching you than you think. Do not forget the importance of also developing and showcasing soft skills like presentation, public speaking, team leadership, in addition to technical ability. **What you can control is perception, drive, making your interests known, and willingness to take the lead.**"

As HKN's MGA Governor At-Large, Jefferies supports HKN because of its ideals, stating that "the universal message of HKN embodied in scholarship, character, and attitude stands the test of time." He remembers his own induction fondly as it opened his eyes "much wider to the profession and idea of the engineering community." He hopes that with HKN's timeless mission and message, it will expand its "recognition of individuals who meet the moment." He challenges Chapters to deepen HKN's meaning by increasing campus visibility and engaging in activities and leadership opportunities that will spread the HKN brand in broader ways through cooperation with student branches and the public.

Jim Jefferies worked at AT&T and Lucent Technologies for 33 years in engineering and executive positions, including fiber optic cable development and manufacturing, quality assurance, and supply chain management. Early interests were in control systems and testing. He managed the engineering teams that designed the first full-scale- manufacturing processes for fiber optic cables at AT&T, transferring glass technology from Bell Laboratories. In quality assurance, he emphasized reliability modeling. As logistics vice president, he focused on the competitive strength of distribution operations as well as the export of US-built products. He also worked in the entrepreneurial sector as Chief Operating Officer for USBuild.com in San Francisco. He received his B.S. in electrical engineering from the University of Nebraska and his M.S. in engineering science from Clarkson University. He attended the Stanford University Graduate School of Business as a Sloan Fellow and completed an MS in Management.

He is a member of Eta Kappa Nu, Tau Beta Pi, and is a registered professional engineer (emeritus) in Nebraska.

Donor Profile

Dave Green Uses Donor Advised Fund Giving to Support HKN

Dave & Bev Green

Dave Green, an alumnus of the Theta Eta Chapter, and his wife, Beverly, have been big supporters of IEEE-HKN throughout the years and proudly state "I am honored to support IEEE-HKN both through advocacy and through donations. IEEE-HKN has improved upon the HKN model by honoring more professionals and instilling a philosophy of service in inductees." One of his chief motivators to give is his favorite HKN memories, "I have been involved in two Chapter start-ups and remember the great support we got from HKN in doing them. The National President came to campus to oversee the first induction ceremony — a great way to start a tradition at the university. I was also fortunate enough to be a very small part of combining HKN with IEEE and seeing the ceremonial signing of the documents formalizing the relationship."

He routinely donates through their Donor Advised Fund (DAF).They include the IEEE Foundation in their DAF Succession Plan and are *Forever Generous* members of the IEEE Goldsmith Legacy League. They said of the decision, "Like everyone with a DAF, we have made a decision to donate, over time, to causes we believe in, like the IEEE Foundation. When it came to designating successors to our DAF, it seemed obvious that we should name a charity to receive the funds rather than having someone else make decisions on directing the funds. The IEEE Foundation was an obvious choice for us. We support the Foundation, its mission, and its programs. For us, it is the perfect choice for the remaining funds."

Originally established in 1931 by the New York Community Trust and supported by John D. Rockefeller, the concept of the DAF has recently taken the nonprofit world by storm. According to data from the National Philanthropic Trust, 1,948,545 individual accounts with more than US$228,890,000 in assets are active in the United States.

As an IEEE-Eta Kappa Nu member, you may have established a DAF to take advantage of the tax benefits and maximize your philanthropic impact. If so, IEEE-HKN (through the IEEE Foundation, an IRS-recognized 501(c)3 organization) can accept disbursements from most DAFs to any of its donor-designated funds. The IEEE Foundation DAF website provides the necessary information to process your gift: https://www.ieeefoundation.org/ways-to-give/donor-advised-funds/.

Have you named a successor for your DAF?

An important part of a DAF owner's estate plan and charitable legacy is deciding where to direct the DAF upon their death. These directions are known as the 'DAF Succession Plan' and involve informing the DAF sponsor how to distribute the remaining balance in the DAF upon the owner's (or owners') passing. The DAF sponsor determines the specific options available to a DAF owner. The most common options related to designating a non-profit, like IEEE-HKN, through the IEEE Foundation, include:

- Naming IEEE-HKN, through the IEEE Foundation, as successor advisor to the DAF
- Naming IEEE-HKN, through the IEEE Foundation, as a full or partial beneficiary of the DAF
- Endowing the DAF to issue grants to IEEE-HKN, through the IEEE Foundation, for as long as possible.
- If you have nominated IEEE-HKN, through the IEEE Foundation, as a successor for your DAF, you are eligible to join the IEEE Goldsmith Legacy League. Let the IEEE Foundation team know at donate@ieee.org to arrange your recognition.

Don't Have a DAF and Curious to Learn? What is DAF?

A DAF is a centralized charitable account that enables charitably inclined individuals, families, and businesses to make tax-deductible charitable donations of cash, publicly traded stock, and, in some cases, certain illiquid assets to a public charity that sponsors a DAF program.

What are the benefits of a DAF?

Establishing a DAF has two main benefits for those looking to make a philanthropic impact. First, when an irrevocable contribution is made to the DAF, an immediate tax deduction can be taken. This gift can be made without a specific designation in mind, which allows a donor to maximize their charitable deduction as part of their financial strategy. Second, the donor invests assets in the DAF per their designated investment strategy, giving the donor the potential to generate even more philanthropic capital. This gives a donor the ability to grow far beyond the initial investment.

How to Establish a DAF?

To establish a DAF, a donor makes an irrevocable contribution to the DAF held by a sponsoring charitable entity and receives an immediate tax deduction. The donor can name their DAF anything they would like; appoint friends and family members to help the donor manage the responsibilities of a DAF; and design a Legacy Plan to determine what will be done with the DAF assets beyond their lifetime, which may include appointing successors or charitable beneficiaries. (Tip: Nominating IEEE-HKN through the IEEE Foundation, as a successor for your DAF also qualifies you for entry into the IEEE Goldsmith Legacy League). What happens to assets within a DAF?

The donor can then invest assets in the DAF per their designated investment strategy, giving the donor the potential to generate even more philanthropic capital. As soon as the DAF is set up, the donor can recommend organizations for grants to be approved by their DAF sponsor. The DAF sponsor can approve grants to most organizations that are tax-exempt under Internal Revenue Code (Code) Section 501(c)(3) and classified as public charities under Code Section 509(a), as well as certain private operating foundations. This typically includes IEEE-HKN, through the IEEE Foundation, but for a comprehensive list, check with your financial services provider.

If you already have a DAF, consider how it can make an impact on IEEE-HKN, through the IEEE Foundation. If you are interested in establishing a DAF, contact your financial services provider. You can learn more about DAF giving online.

The information in this article is for educational purposes only and is not intended as legal, tax, or investment advice. If you are considering establishing or making a gift from a DAF, we highly recommend you consult with your own tax and legal advisors to determine the best options for you.

IEEE Nuclear and Plasma Sciences Society

John Verboncoeur (Michigan State University), Randy Curry (Sandia National Laboratories), and Martin Nieto-Perez (Penn State University)

Overview of NPSS

The IEEE Nuclear and Plasma Science Society (NPSS) is a federation of areas in the nuclear and plasma science and engineering spaces. Eight technical committees represent the areas:

- Computer Applications in Nuclear and Plasma Sciences (CANPS): Fields of interest are real-time and off-line computer systems, including hardware and software aspects of data acquisition, data analysis, data storage, and control, in any and all of the technical disciplines covered by the NPSS. The biennial Real-Time Conference is run by CANPS Fusion Technology Committee (FTC): This committee covers the technology of both inertial and magnetic confinement fusion experiments, which are leading to a better understanding of the requirements for a fusion reactor and for an environmentally benign, virtually limitless source of energy for electric power and industrial uses. This committee organizes the biennial Symposium on Fusion Engineering. This committee also supports the IEEE USA Energy Policy Committee in the preparation of energy-related white papers.
- Nuclear Medical and Imaging Sciences Committee (NMISC): The field of interest of the committee is nuclear medical and imaging sciences, and their related technologies and applications. NMISC and RITC cosponsor the IEEE Nuclear Science Symposium, Medical Imaging Conference, and Room-Temperature Semiconductor Detectors Symposium.
- Particle Accelerator Science and Technology: The field of interest is the science and engineering of particle accelerators. In collaboration with the American Physical Society Division of Beam Physics, PAST cosponsors the xPAC series of conferences.
- Plasma Sciences and Applications Committee (PSAC): This committee deals with research and development of the plasma state of matter. Since plasmas are conductive, responding to electric and magnetic fields, they are usable in numerous applications where such control is needed or when special sources of energy or radiation are required. PSAC runs the International Conference on Plasma Science.
- Pulsed Power Science and Technology (PPST): This committee covers pulsed power science and technology. and its application in many areas of high power technologies. PPST runs the biennial Pulsed Power Conference.
- Radiation Effects (REC): This committee advances the theory and application of radiation effects and its allied sciences, with important implications for electronics in space, medical systems, nuclear power plants, and other challenging environments. REC runs the biennial RADiation Effects on Components and Systems (RADECS) Conference.
- Radiation Instrumentation Technical Committee (RITC): The field of interest is the development and application of radiation detectors, radiation instrumentation, nuclear electronics, and measurement techniques for ionizing radiation. The NMISC and RITC cosponsor the IEEE Nuclear Science Symposium, Medical Imaging Conference, and Room-Temperature Semiconductor Detectors Symposium.

NPSS publishes four journals:

- *Transactions on Medical Imaging:* jointly published with the IEEE Engineering in Medicine and Biology Society,
- *Transactions on Nuclear Science*
- *Transactions on Plasma Science*
- *Transactions on Radiation and Plasma Medical Sciences*: Jointly published with the IEEE Engineering in Medicine and Biology Society.

Fusion Activities

NPSS has many activities related to fusion energy distributed among the technical committees above. We will focus on a few of these, primarily through the FTC and the PPST.

The goal of fusion energy is to bring the power source of the Sun to Earth, with the potential for zero carbon emissions, a copious fuel source in naturally occurring heavy water, and a far lower radiation load compared to nuclear fission. The ability to supply steady baseload levels of power in a far smaller footprint than solar and wind without the time-variability is another key benefit.

Technically, the fusion process presents a daunting challenge due to the temperatures involved. To overcome the electrostatic repulsion between two positively charged nuclei, the gas that serves as fuel, a mixture of deuterium and tritium needs to be heated to temperatures of tens of keV, which translates to hundreds of millions of degrees Celsius. The technical hurdles associated with keeping matter at such high temperatures are indeed daunting. To begin with, no material can withstand direct contact with gas heated to those exceptionally high temperatures. This led to the development of specialized "magnetic bottles," taking advantage of the fact that at such high temperatures any gas is a fully ionized plasma. A magnetic field can be generated, which keeps the superhot plasma from touching any physical object. The tokamak, a Soviet design, and the stellarator, a U.S. design, are two of the most developed concepts to achieve this magnetic confinement.

Physics and technology challenges inhibited the realization of fusion for over 50 years, but recent advances in each have resulted in rapid progress recently. Over $6 billion in private funding and over 60 companies have added to the historically government-supported efforts. The plasma physics processes involved in controlled nuclear fusion are well understood thanks to the advent of high-performance computing to improve plasma simulations and modeling. Artificial intelligence and machine learning have helped overcome the control challenges of keeping plasma confined for extended periods. The now readily available high-temperature superconductors allow the production of much stronger magnetic fields more economically. Additive manufacturing enables the production of components deemed unfeasible in the past with unprecedented precision. This progress has accelerated both magnetically (such as ITER) and inertially confined fusion (such as the National Ignition Facility, which achieved a net positive energy release in 2023).

The field of pulsed power is unique for it compresses the low current and modest voltage of a wall plug, power supply, into peak pulsed powers, which today can generate megavolts and megamperes of current in 100-200 ns as well as microsecond pulsewidths. Thus, energy storage and high voltage switches that operate at these high peak powers are required for fusion energy. As well as pulsed power circuits and components that can operate repetitively in a fusion power plant, once fusion energy sources are developed.

The most popular ICF approach to-date is the National Ignition Facility (NIF) at LLNL. NIF utilizes 192 laser beams focused onto the wall of a Hohlraum. The cryogenically cooled D-T pellet is suspended in the Hohlraum and heated by X-rays generated at the wall of the Hohlraum. The surface of a deuterium-tritium pellet is ablated by the absorption of the X-rays generated by the laser beams on the Hohlraum wall. In fact, the surface of the pellet is heated to over 3 million degrees Celsius.

An alternative approach is the direct drive, pulsed power approach utilized at SNL for the Z machine. Approximately 20 MJ of capacitors are slowly charged and then discharged. The Marx capacitor topology of the Z machine is comprised of 36 modules of which the energy is equally portioned. The terawatt class pulsed power machine discharges approximately 22 MA into the loads, many of which are being used to investigate and scale fusion processes. The next generation of pulsed power machines will be designed to discharge 60 MA into the fusion energy load.

Significant engineering challenges with each approach remain. The aspects related to materials and configurations to manage massive heat fluxes at surfaces, high-strength low-energy magnetic fields for confinement, particle and wave systems for energy deposition, and active control systems to manage instabilities are all key topics in NPSS, including FTC, PPST, and PSAC. We look forward to your engagement!

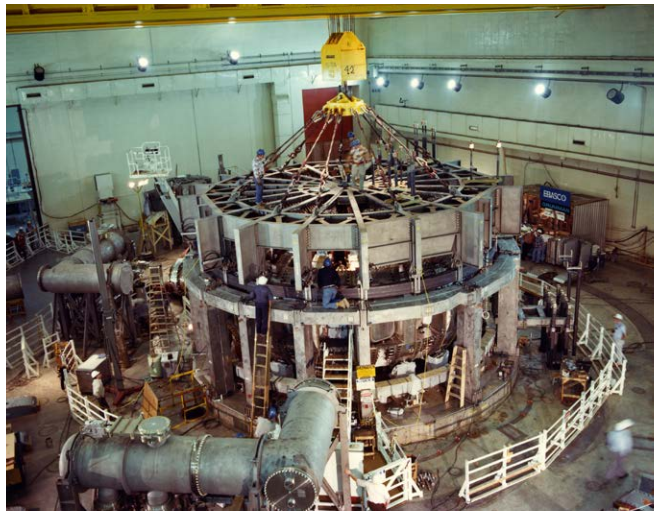
30 Years to Fusion: A Historical Perspective

Hannah Pell and Matthew Parsons

On March 1st, 1979, NOVA aired an episode titled *The End of the Rainbow,* examining the promises and problems of fusion as a viable energy solution for the future [1]. Thirteen minutes in, viewers were presented with a timeline: "Scientific Feasibility" (energy out equals energy in) expected by the U.S. Department of Energy (DOE) before 1985; "Technological and Engineering Feasibility" (more energy out than in, with some energy converted to electricity) by 2005; and "Economic Feasibility" (a pilot fusion plant operating reliably and economically) by 2015. In an arc spanning only three decades, it claimed scientists and engineers would reach the elusive pot of gold - unlimited clean energy.

"Yet, if all these stages succeed, it could still be 30 more years before fusion could make a nation-wide impact," the narrator promptly cautioned.

Any historian who is, by definition, an authority on timelines might find the 30-years-to-fusion claim suspect, considering such a multi-decade estimate has persisted at least since the inaugural 1955 Geneva Conference, in which Atoms for Peace Chairman Homi Bhaba (more optimistically) predicted, "A method will be found for liberating fusion energy in a controlled manner within the next two decades." [2] A review published in the *Journal of Fusion Energy* last year determined the adage should be amended to: "Fusion was said to be 19.3 years away 30 years ago; it was 28.3 years away 20 years ago; 27.8 years away 10 years ago." [3]



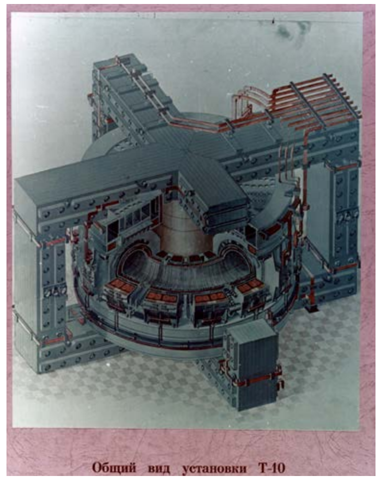
Tokamak Fusion Test Reactor (TFTR) during construction at Princeton University. Credit: Princeton Plasma Physics Laboratory, courtesy of AIP Emilio Segrè Visual Archives

However, recent developments suggest the end of the rainbow may actually be right around the corner. The latest laboratory breakthrough, a laser-powered reaction that exceeded "scientific breakeven" at the National Ignition Facility (NIF) in December 2022 and has since been replicated [4], has reignited excitement (and investments) in fusion's near-term viability. Private start-up companies touting aggressive plans for electricity production within the 2030s seek more money in order to get more energy out [5]. It's been 45 years since the NOVA episode aired, and it appears that all the stages are succeeding, yet a familiar caution is evident: "The momentary fusion feat [at the NIF] required exquisite choreography and extensive preparations, whose high degree of difficulty reveals a long road ahead before anyone dares hope a practicable power source could be at hand," *IEEE Spectrum* observed [6]. Perhaps looking back on the long road of fusion behind us can help explain why it still seems to remain just as distant today.

At the 1964 World's Fair, the General Electric exhibit *Progressland* included an attraction called Fusion on Earth, the first demonstration of controlled thermonuclear fusion witnessed by a general audience. "The experimental device does not produce any useful electricity itself… At present, this goal remains beyond the capabilities of modern technology," The New York Times reported [7]. Such "modern technology" was the early stages of competing fusion reactor designs - the Z- and theta-pinch, stellarator, and tokamak. The 1958 declassification of ongoing fusion research accelerated the international race to achieve it, primarily between the United Kingdom with its Zero Energy Thermonuclear Assembly (ZETA), of which an infamous January 1958 claim that fusion had been achieved but was disproven shortly thereafter caused a serious setback to the credibility of early fusion research; the U.S. theta-pinch Scylla experiment at Los Alamos National Laboratory and stellarator at Princeton; and the former Soviet Union's tokamak, which was ultimately proven the superior design in 1968.

Though the next two decades saw a flurry of conversions to the tokamak design and subsequent upgrades to achieve even higher energies, it quickly became clear that new engineering challenges were beyond the capability of one country to solve on its own. General Secretary Gorbachev of the former Soviet Union proposed the idea of international fusion collaboration to President Ronald Reagan at the November 1985 Geneva Superpower Summit, 30 years after physicist Homi Bhaba's fusion prediction at the first conference. An agreement between the United States, former Soviet Union, European Union and Japan was reached soon thereafter to pursue the International Thermonuclear Experimental Reactor (ITER, meaning "The Way" in Latin), for the purpose of demonstrating the scientific and technical feasibility of fusion power, not to produce it for commercial supply.

It would take another 30 years to formally sign the ITER Agreement in 2006. Delays accrued initially due to conceptual design challenges for what will be the largest tokamak in the world, as well as disagreements over the machine's location and changing political landscapes which caused uncertainty in funding support. More delays have accumulated since 2006 for varied reasons: design challenges, issues with fabrication of the machine's unique components, and supply chain complications. Notably, in 2022, France's Nuclear Safety Authority determined that the design for radiological shielding to surround the reactor would be inadequate to protect personnel when operations begin, but the addition of more shielding may cause the assembly to exceed the capacity of its earthquake-resistant foundation. Even with the anticipated schedule readjustment to offset the delays with an acceleration of the planned research program, deuterium-tritium operation is not expected to begin much earlier than 2035 -- nearly 30 years after the agreement was signed.



Drawing of the T-10 Russian tokamak fusion reactor device. Credit: AIP Emilio Segrè Visual Archives, Physics Today Collection

As the work at ITER continues, fusion research in the U.S. has pressed on at the NIF, which similarly underwent significant schedule delays and cost overruns during its construction at the Lawrence Livermore National Laboratory in the early 2000s. Although the experiment utilizes an inertial confinement approach designed for weapons research rather than electricity generation, the December 2022 "Wright brothers' moment" has been used by industry as an example of significant progress to further accelerate commercial fusion's current political hype [8]. This optimism is further organized and trumpeted by the Fusion Industry Association (FIA), a D.C.-based nonprofit established in 2018 as the voice of the private fusion industry, currently advocating on behalf of over 30 companies. In response, the rules are changing to accommodate -- last year, the Nuclear Regulatory Commission decided that fusion technologies will be licensed separately from the regulatory framework for fission reactors.

The stars appear to be aligning once again for the future of fusion energy, but the constellation is familiar. "We are all deeply accustomed to seeing science as the one enterprise that draws constantly nearer to some goal set by nature in advance," wrote Thomas Kuhn in *The Structure of Scientific Revolutions* [9]. Though there has been undeniable progress over the decades of fusion research undertaken thus far, in-part due to advances in supercomputing and the commercial availability of high-temperature superconducting tapes, achieving the revolutionary dream of unlimited clean energy will not only require technological advancements funded by extraordinary economic resources, but a shared prioritization of fusion power as the answer to combatting our climate crisis.

So, how far away is fusion? At least one answer is certain: about 93 million miles.

Hannah Pell is a science writer interested in the history of physics and the energy industry. She works in nuclear licensing and compliance.

Matthew Parsons is a research physicist developing heat exhaust solutions for fusion reactors. He has worked on projects ranging from table-top experiments to the world's largest fusion experiment (ITER).

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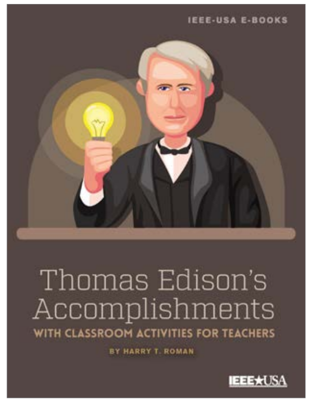
IEEE-USA's Free New March E-Book for Members Promotes STEM Education Using Edison's Accomplishments

Georgia C. Stelluto

WASHINGTON (1 March 2024)—*"As children work their way through the engineering design process, and work in student teams in their STEM classes, they are mimicking what Edison and his staff did in creating the cornucopia of products that emanated from his labs and factories."*

—Harry T Roman, Inventor, Educator, and IEEE-USA E-Book Author



Harry T. Roman has written several books for teachers, laying out creative ways to engage and stimulate students about STEM. In his new IEEE-USA e-book, ***Thomas Edison's Accomplishments with Classroom Activities for Teachers***, Roman highlights Edison's achievements and provides suggested activities to promote to teachers, parents, and students how Edison is linked to STEM.

Roman firmly believes that Edison deserves special recognition in STEM education. "As children work their way through the engineering design process and work in student teams in their STEM classes, they are mimicking what Edison and his staff did in creating the cornucopia of products that emanated from his labs and factories," he said.

In addition, Roman has written three IEEE-USA e-books on Thomas Edison's life, serves as an advisor and author to the Edison Innovation Foundation, and is active as a docent and special lecturer at the Thomas Edison National Historical Park.

Members: Download your free e-book, by going to: https://ieeeusa.org/product/thomas-edisons-accomplishments-with-classroom-activities-for-teachers/

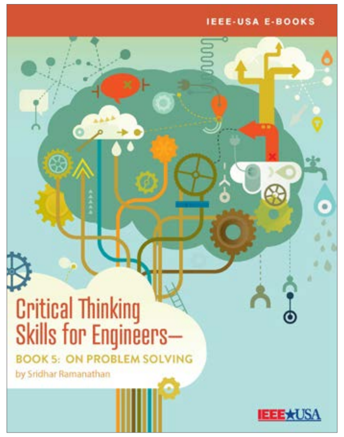
Non-members pay $2.99. Search for Roman's many other titles promoting STEM and creativity in the classroom (for members only) in the IEEE-USA Shop.

Log in to your IEEE Web Account; add the book to your cart -- and checkout! No promo code necessary!

Check out the full article at IEEE-USA InSight at: https://insight.ieeeusa.org/articles/driving-stem-education-using-edisons-accomplishments/

IEEE-USA's March Free Audiobook for Members Examines New Ways to Tackle Problems

WASHINGTON (1 March 2024)—*"A problem well stated is a problem half solved."* —Charles Kettering, Head of Research, General Motors -- 1920-1947



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